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AN EVALUATION OF POTENTIAL COUNTERMEASURES
TO THE
STRATEGIC DEFENSE INITIATIVE

by

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An Evaluation of Potential Countermeasures
to the
Strategic Defense Initiative

by

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requirements for the degree of

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ABSTRACT

The key uncertainty within the Strategic Defense Initiative is not whether a multitiered ballistic missile defense can be designed and implemented but rather in the possibility that the intercept system can be readily countered. Additionally, the viability of SDI is dependent upon its cost effectiveness; a defense should not be considered if it can be overcome at a significantly lesser cost.

To quantify these uncertainties, the Strategic Defense Initiative is overviewed at a macro level. Potential countermeasures to proposed defensive technologies are defined and analyzed as to their feasibility and the possible leverage, both in cost and in further uncertainty, that the use of the countermeasure would provide. The study also addresses possible counter-countermeasures, where applicable. The results of the study can be used to provide input parameters to systems simulations and system analyses of SDI architectures and as an indicator of further study areas.

TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

In his historic speech of March 23, 1983, President Ronald Reagan tasked the scientific community of the United States to utilize its talent in research towards rendering nuclear weapons "impotent and obsolete." This effort, known as the Strategic Defense Initiative (SDI), has been much discussed in open literature by both scientists and politicians alike. As a result of these interchanges, numerous questions and doubts have arisen as to the goals and feasibility of strategic defense.

A major element of the discussions has been the concept of a layered space-based defense against ballistic missiles. The key uncertainty within the Strategic Defense Initiative is not whether such a multitiered ballistic missile defense (BMD) can be designed and implemented but rather the possibility that the intercept system could be readily countered. Additionally, the viability of SDI is dependent upon its cost effectiveness; a defense should not be considered if it can be overcome at a significantly lesser cost. To quantify these uncertainties, possible countermeasures to currently proposed SDI technologies and architectures will be defined. These countermeasures will be analyzed at a macro level as to their feasibility and the leverage, both in cost and further uncertainty, that they would provide.

This report is a compilation of analyses, drawn from open literature, of the potential technologies and architectures of SDI and of the resulting potential countermeasures. It will provide the decision maker with a system level understanding of the major issues of SDI and provide a basis for comparing the different technologies. The results of the study could be used to provide input parameters to system simulations and system analyses of SDI architectures and as an indicator of further study areas.

II. THE GOALS OF SDI

An intense dialog as to the ultimate goal of SDI was the immediate response to President Reagan's "Star Wars" speech. Many of the arguments were the same as those which arose during the debates of the late 1960's and early 1970's on the Sentinel and Safeguard Antiballistic Missile (ABM) systems which resulted in the 1972 ABM Treaty. An understanding of the possible goals of SDI is required in order to evaluate the effectiveness of the various proposed architectures.

A. PERFECT DEFENSE

The purpose of the Strategic Defense Initiative, as stated by President Reagan within his "Star Wars" speech, is to start a "comprehensive and intensive effort to define a long term research and development program to achieve our ultimate goal of eliminating the threat posed by strategic nuclear missiles." [Ref. 1: p. 86] The many critics of SDI read this statement to mean that the administration is advocating the development of a thoroughly reliable, 100% effective, perfect defense of both civilian population and military assets against all nuclear weapons. This effort would change the United States' strategic policy from one of mutual assured destruction to one of assured survival.

However, within the National Security Decision Directive implementing the program, the President clarified that his desire was "to decrease our reliance upon the threat of retaliation by offensive nuclear weapons and to increase the contribution of defensive systems to our security and the security of our allies." [Ref. 2] Further, at a recent conference on space and national security, Lieutenant General James Abrahamson, the director of the SDI program,

acknowledged that "there is no perfect weapons system, there is no panacea," and Dr. Gerald Yonas, the program's chief scientific advisor, said that the program's only purpose is to "search for technology to see if we can find an alternative to the present system." [Ref. 3]

B. LESS-THAN-PERFECT DEFENSE

Given that a perfect defense is unattainable, a number of other defensive goals become plausible.

1. Enhance Deterrence

A limited defensive capability would enhance deterrence against nuclear war in essentially three ways. Primarily, as an indeterminable number of offensive missiles could no longer reach their designated targets, Soviet military planners would face increasing uncertainty and difficulty in planning a successful attack. Second, even a moderately effective defense would force an opponent to expend a larger number of offensive weapons than currently required to achieve the same result. Finally, some high value targets, such as intercontinental ballistic missile (ICBM) silos, may become invulnerable to a preemptive first strike. Therefore, for all these reasons, the military utility of such a strike would be degraded.

2. Assure Retaliatory Capability

An effective preferential defense of the United States' MX and Minuteman ICBM silos and command centers would provide the U.S. with an assured retaliatory capability. How and when such a capability would be used is a complex political problem. However, if this is to be considered a valid goal of SDI, the feasibility studies conducted prior to 1972 for the Sentinel/Safeguard ABM systems should be seriously reconsidered. An ABM defense designed to protect only missile silos and command centers could possibly be done at the terminal end alone and therefore a space based system may not be cost effective. Terminal

defense methods such as dispersal, silo hardening, mobility, and preferential defense strategies have also been suggested to keep the retaliatory missiles invulnerable.

TABLE I

EFFECTS OF A SINGLE 0.5-MT WEAPON (AIRBURST) ON THE TEN LARGEST U.S. URBAN AREAS

Metropolitan Areas	Population in 1970 (millions)	Fatalities (millions)	Casualties (millions)
New York	16.3	1.2	3.3
Los Angeles	8.7	0.4	1.1
Chicago	6.7	0.9	1.9
Philadelphia	4.6	0.4	1.4
Detroit	3.9	0.5	1.3
San Francisco	3.6	0.5	0.8
Boston	2.9	0.5	1.1
Washington	2.6	0.4	1.1
Miami	2.3	0.3	0.7
Dallas	2.1	0.2	0.5
Total	53.7	5.3	13.2

NOTES:

a. Source: U.S. Arms Control and Disarmament Agency, U.S. Urban Population Vulnerability, (GPO, 1979).
b. Assumptions: attack is designed to maximize human fatalities; fatalities are prompt only, using usual overpressure-casualty relationships; residents are in their homes at the time of attack.
c. The effects of a multi-weapon airburst would be initially synergistic.

3. Save Lives

"Wouldn't it be better to save lives than to avenge them ?" This noble thought, quoted from President Reagan's "Star Wars" speech, has set the tone for the continuing debates over SDI. Some critics of the program argue that to attempt to replace the current strategic deterrence posture with defense is sheer folly. They argue that, even if the U.S. technology base were able to develop a defensive system that was 95% effective, this very accomplishment would force

the Soviet Union to change its offensive strategy from an attack on military targets to a concentrated attack on population centers in the hope of forcing the U.S. government to capitulate without a retaliatory effort. The resulting population damage would be catastrophic, as shown in Table I. However, as General Daniel O. Graham, USA (Ret), has stated, "It is a strange moral and political logic that argues that because we cannot save everyone we should abandon all efforts to save anyone." [Ref. 4] Again, this is a political problem which is nonquantifiable to the decision maker yet must be considered as a goal of SDI.

4. <u>Slow the Pace of Conflict</u>

An effective defense against ICBMs may pressure the Soviet Union to shift the makeup of their offensive forces towards submarine launched ballistic missiles (SLBM), cruise missiles, and bomber aircraft. U.S. military planners would rather confront these slower flying weapons, which allow more time for response, than confront the fast flying ICBMs. Additionally, the slow flying cruise missiles and bombers would be arguably easier to shoot down than an ICBM.

5. <u>Prevent Accidents and Small Strikes</u>

A defense designed to counter a full scale Soviet offensive would also be effective in preventing smaller nuclear exchanges. These exchanges could be classified into three general groups :

- accidental nuclear missile launches,
- attacks by smaller nuclear powers,
- limited, high confidence, bargaining strikes during crises.

C. OTHER GOALS

Some skeptics have suggested that the current military and civilian administrations had ulterior goals other than defense in putting forth the Strategic Defense Initiative.

1. <u>Provide the U.S. with a First Strike Capability</u>

a. SDI as an Offensive Weapon

Should the technologies proposed for strategic defense mature into realistic systems, it would be an easy step to move from strategic defense to strategic offense. The system which is capable of intercepting ICBMs shortly after takeoff may also be capable of destroying targets on the ground. Additionally, there exists a close similarity in the technologies proposed for ballistic missile defense and those proposed as anti-satellite (ASAT) devices. An attack against Soviet military satellites would be a logical precursor to a U.S. first strike.

b. SDI as a Shield from Retaliation

A modest, imperfect defense may be better utilized as an adjunct to an attacking force than as a defense against attack. While not capable of providing a defensive shield against an all out Soviet offensive, a modest defense could be capable of protecting the U.S. against a ragged retaliatory effort by the Soviets after a U.S. first strike.

2. <u>Respond to Soviet BMD Efforts</u>

U.S. military leaders have often declared that the Soviet Union has continued with its own BMD efforts despite the ABM Treaty and SALT agreements. The most recent potential violation is a phased array radar currently under construction at Krasnoyarsk within the Soviet Union. Military sources also state that the USSR is upgrading the ABM system protecting Moscow with new missile, detection, and tracking systems. These developments indicate that the Soviets are maintaining active research in BMD technology. Should the U.S. not implement its own research effort, she may find herself unable to compete with the Soviets during future periods of conflict.

3. Shape the Course of Arms Control

The mere idea of a defensive posture by the United States has brought the Soviets back to the arms control table after years of stonewalling. Also, the SDI program has provided the U.S. with great bargaining power, as evidenced by the Soviet response during the recent arms control talks. If the ongoing research studies prove SDI to be a feasible project, the U.S. may gain a degree of strategic leverage that she has not had since the advent of nuclear weapons. This leverage would allow the U.S. to direct future arms competition and arms control to her own ends.

4. Alter Economic States

Some Soviet officials suspect that by instituting a highly sophisticated and expensive defense program, Washington hopes to force Moscow into an arms race which will severely tax their resources and technological capabilities. This action in itself may add to nuclear deterrence. If the current research shows SDI to be feasible, the Soviets may find that the increased level of offensive weaponry needed to wage a successful first strike is unreasonable on economic terms.

Another area of impact by SDI would be the American economy. The massive amount of funding that the implementation of SDI is expected to require would provide benefits in terms of employment, large investments, expanded use of technology, etc. Additionally, one must consider the possible long run savings the U.S. would experience by stemming the currently unbridled arms race.

D. MEASURES OF EFFECTIVENESS

The measures of effectiveness (MOEs) of a program like SDI are dependent upon the program's specific goals. Examples of possible MOEs are :

- the number of American lives saved by the system,
- the number of retaliatory missiles available to the U.S. after a Soviet first strike,

- the leakage allowed by the system,
- the period of time without a nuclear interchange between superpowers.

Numerous other, more definitive measures could easily be determined. However, which of these MOEs are pertinent is a political decision which will not be addressed within this study.

A significant problem in determining the effectiveness of a defensive system lies behind the fact that such a system can never be fully tested. In the face of a total Soviet offensive, the system would be expected to respond immediately and flawlessly. Therefore, regardless of the goal, considerable uncertainty will always remain as to the system's effectiveness.

III. DEFINING THE THREAT

Primary in the design of a defensive military system is the definition of the threat to be countered. The scope of the threat is driven by the goals of the system and vice versa. If the goal of SDI is strictly to provide an effective strategic defense, then only those weapons and weapons platforms capable of delivering a long range strategic nuclear strike should be considered.

These weapons and platforms will be quantified at current levels; however, the decision maker must realize that it is not current levels but future and potential levels against which the effectiveness of any proposed defensive architecture must be judged. Additionally, the threat posed by strategic nuclear weapons, particularly by ballistic missiles, depends upon the method by which the weapons are deployed and utilized. Perhaps the most pertinent criteria for the decision maker is that the defensive system must be designed to operate effectively under full stress--that is, to effectively perform when faced with a simultaneous launch of all available offensive assets while these assets are employed in a manner which is advantageous to the opponent.

A. CURRENT THREAT

While a growing number of nations are capable of launching strategic nuclear weapons, the Soviet Union poses the most significant threat to the United States. The Soviet Union is capable of placing strategic nuclear weapons upon U.S. soil via intercontinental ballistic missiles, submarine launched ballistic missiles, long range strike aircraft, and long range cruise missiles. If the goal of providing an effective defense includes defending the assets of the U.S.

and its allies within Europe, then the Soviet intermediate range ballistic missiles (IRBM) must also be taken into account.

The following tables show current Soviet strategic force levels as recently reported by the Department of Defense. Table II provides strategic missile levels with the corresponding number of warheads. Equally as important as the number of missiles is the number of platforms from which the weapons can be launched. Table III provides this information. Knowledge of the number, disposition, and location of the weapons platforms is essential to an effective defense. The numbers and locations of hardened ICBM silos and operational bomber squadrons is readily determined and verified prior to launch via intelligence methods. However, trends in current Soviet modernization and expansion show a shift from this state towards mobile ICBM launch platforms and bomber aircraft using stealth techniques which will obviously be harder to plan and design against. The more difficult problem is determining the status of submarine strategic launch platforms. As the Soviet Union continues to upgrade the capabilities of its SLBMs, increase the number of its submarine launch platforms, and exercise long term operational deployment schedules, the threat posed by the Soviet submarine fleet may become the driving factor of any defensive architecture.

B. FUTURE THREAT

In consideration of the long developmental period required by any new weapons system, the designers and decision makers of SDI need to look far into the future when attempting to assess the threat which will be faced. While trying to look this far ahead is difficult, one can look at the Soviet strategic developments of the recent past and the near future to attempt to extrapolate into the outyears. A prudent decision maker should assume that Soviet development

TABLE II

SOVIET STRATEGIC MISSILE LEVELS

	Type	Number Deployed	Number Warheads
ICBMs :			
	SS-11 Mod 1	100	1
	SS-11 Mod 2/3	420	1-3
	SS-13 Mod 2	60	1
	SS-17 Mod 3	150	4
	SS-18 Mod 4	308	10
	SS-19 Mod 3	360	6
	Total	1398	6420-7260
SLBMs :			
	SS-N-5	42	1
	SS-N-6 Mod 1/2/3	336	1-2
	SS-N-8 Mod 1/2	292	1
	SS-N-17	12	1
	SS-N-18 Mod 1/2/3	224	1-7
	SS-N-20	60	6-9
	Total	966	1266-3126
IRBMs :			
	SS-4	79	1
	SS-20	441	3
	Total	520	1402
Long Range Cruise Missiles :			
	AS-15	-	1
	Grand Total	2884	9088-11788

NOTES :

a. Source: Department of Defense, Soviet Military Power 1985, (GPO, 1985).
b. The number of long range cruise missiles is unavailable due classification limitations.

will at least continue at present pace and probably increase in order to undermine U.S. efforts to transition to a defensive posture.

Since the SALT I Interim Agreement of Offensive Arms of 1972, the Soviet Union has increased its offensive forces both quantitatively and qualitatively to the fullest extent possible within the constraints of that agreement and the follow-on SALT II Agreement. U.S. military officials have

TABLE III

SOVIET STRATEGIC LAUNCH PLATFORMS

Long Range Strike Aircraft :

Type	Number	Unrefueled Combat Radius (kilometers)	Maximum Speed (knots)
Bear (TU-95)	125	8300	500
Backfire B	250	5500	1100
Bison M	48	5600	540
Badger (TU-16)	287	3100	540
Blinder (TU-22)	136	2900	800
Total	846		

Ballistic Missile Submarines :

Type	Number Deployed	Number Missiles	Missile Type
Yankee I	21	16	SS-N-6
Yankee II	2	12	SS-N-17
Delta I	36	12	SS-N-8
Delta II		16	SS-N-8
Delta III		16	SS-N-18
Typhoon	3	20	SS-N-20
Total	62	928	

NOTES :

a. Source: Department of Defense, Soviet Military Power 1985, (GPO, 1985).
b. The intercontinental Bear and Bison bombers are available for maritime and Eurasian missions. The Backfire bomber can be used against the continental U.S. The remaining platforms are available for in-theater missions.
c. Submarine totals do not include 13 older generation submarines equipped with 38 missiles which are currently assigned theater missions. Accounting for these missiles provides the 996 missile total of of Table III.

also been given reason to believe that in some areas the Soviet Union may have violated the tenets of those agreements. Since 1971, Soviet strategic offensive forces introduced include :

- four new types of ICBMs
- five new types of ballistic missile submarines
- four new types of SLBMs

- five improved versions of existing SLBMs
- long range cruise missiles
- long range bomber aircraft capable of firing air-launched cruise missiles

Numerically, during this period the Soviet Union deployed 62 new ballistic missile submarines, virtually all its current ballistic missile submarine fleet. The Soviets also introduced their entire complement of multiple, independently targeted warhead ICBMs, including the SS-17, SS-18, and SS-19. The liquid fueled SS-18 is the largest missile currently deployed by any military power and is capable of carrying ten warheads. The smaller SS-17 and SS-19 carry four and six warheads, respectively. It is interesting to note that deployment of these ICBMs began merely seven years ago. In comparison, the most modern U.S. missile, the Minuteman III, is capable of carrying only three warheads. The U.S. is, however, developing a new missile, the Peacekeeper/MX, which will be capable of carrying ten warheads. None of these missiles are currently deployed.

The Soviet Union also has a number of new systems under development and nearing deployment. These systems include :

(1) New fourth and fifth generation ICBMs. The medium sized SS-X-24 will be capable of carrying up to ten warheads and the smaller SS-X-25 will carry one warhead. These missiles show large advances in Soviet technology in that both missiles will be solid fueled. Additionally, a mobile version of each of these systems will be deployed, thereby strengthening the Soviet strategic posture. The SS-X-25, if deployed, will violate the SALT II Agreement which limited both sides to developing only one new type of ICBM.

(2) A new generation SLBM. The SS-NX-23 is a large, liquid propelled missile which will have greater range, carry more warheads, and be more accurate than the SS-N-18 currently carried aboard the Delta III class submarine.

(3) A new class of nuclear powered ballistic missile submarine. The Delta IV will carry sixteen SS-NX-23 ballistic missiles.

(4) A new long range bomber. The Blackjack has been estimated to have an unrefueled combat radius of 7300 kilometers and a maximum speed of 1100 knots. The aircraft will be capable of carrying cruise missiles,

bombs, or a combination of both. The Blackjack will be capable for use against the continental U.S. and may be operational by 1988.

(5) Four new types of cruise missiles. Two of the missiles are adaptations of the air launched AS-15 currently in the Soviet inventory. The SS-NX-21 will be submarine based while the SSC-X-4 will be ground based. Each of these carry a single warhead and have a range of 3000 kilometers. The remaining two cruise missiles under development are the submarine launched SS-NX-24 and the ground launched GLCM. These missiles are considerably larger than any previous cruise missile and are estimated to be extremely accurate.

In addition to these new systems, the Soviets may also choose to upgrade their current systems. For example, the SS-18, while limited by SALT II to 10 warheads, may be capable of carrying up to 30 warheads.

When considering future force levels, allowance can be made for arms limitation agreements, those current and those proposed for the future. Presently, the ABM Treaty of 1972, the SALT I Agreement of 1972, and the SALT II Agreement of 1979 are all still in effect. In the recent arms limitation talks in Geneva, other numerous limitation proposals were offered by both sides. The latest U.S. proposal included a ban on mobile land-based ICBMs and a limitation by both sides to 6000 strategic warheads. Of these, 3000 could be on ICBMs, 1500 on SLBMs, and the remaining 1500 on cruise missiles.

Two major sticking points arose during the recent talks. The Soviets wanted the Strategic Defense Initiative to be up for negotiation, to which the United States objected. The U.S. disagreed to the Soviet proposal for the definition of strategic forces. The Soviets wished to include U.S. Pershing II IRBMs and U.S. ground launched cruise missiles deployed in Europe but not the Soviet SS-20 IRBMs. The reasoning behind this proposal was that the U.S. missiles could reach the Soviet Union but the Soviet missiles cannot reach the United States and therefore should not be considered strategic.

C. THREAT PROFILES

The flight characteristics of the various ICBM, SLBM, IRBM, and cruise missiles provide the structure around which a defense must be designed.

1. Ballistic Missiles

Ballistic missiles are characterized by the free fall trajectory that they follow. Essentially, these missiles rise above the atmosphere, reach a peak height (apogee), and fall back to the earth, pulled by gravity. Via this method, the missiles can rapidly travel over large distances while their trajectory places them out of the reach of current conventional defensive weapons.

The flight path of a ballistic missile can be broken down into four major phases : boost, post-boost, midcourse, and terminal. The weight and size of the missile, the number of warheads carried, the class of propellant (liquid or solid fueled), and the type of launch platform determine the length and character of each phase. Since the Soviets are trending toward solid fueled, multiple warhead missiles analogous to the developing Peacekeeper/MX, the threat profile of the MX will be used for illustration.

The boost phase consists of the time period from when the missile leaves the surface of the earth until the last of its propellant is expended. The missile is initially ejected from its silo by steam pressure. Once clear, a first stage booster rocket ignites and propels the missile upward along a preordained path until the rocket is spent and detaches from the missile structure. Modern ballistic missiles may have up to three such stages with the flight path chosen to require minimum energy. The boost phase typically last several hundred seconds, during which the missile accelerates to about 7 km/sec and reaches an altitude of approximately 200 kilometers. Table IV shows the approximate boosting stages of the MX ICBM. Of note, the last seconds of

the third stage are extremely crucial in order to give the missile enough impetus to reach its intended target.

TABLE IV

MX BOOST PHASE CHARACTERISTICS

Stage	Elapsed Time (secs)	Height (km)
Launch	0	0
First Stage	55	22
Second Stage	110	82
Third Stage	170-180	200

NOTES :

a. Source: Office of Technology Assessment, Directed Energy Missile Defense in Space, April 1984.
b. All numbers are approximate.

Once the rocket boosting is completed, the remaining missile structure (known as the "bus") begins to release a number of warheads throughout the post-boost phase. Each warhead is encased within a vehicle which is shaped and hardened to withstand reentry into the atmosphere. The bus is equipped with small rocket thrusters which allow it to make relatively small course changes in order to release the vehicles into extremely precise ballistic trajectories. Along with the vehicles, the bus can also release a number of decoys and other aids to confuse any defensive target tracking. This type of system is called a multiple independently targeted reentry vehicle (MIRV) system and enables one offensive missile to engage several potential targets. The post-boost phase lasts approximately 500 seconds until the last warhead and decoys are released just prior to apogee.

After all reentry vehicles (RVs) and penetration aids (penaids) are released, the midcourse phase begins. By

this time a defense is not threatened by a single missile but rather by a dense threat cloud comprised of up to 10 RVs and possibly over 100 penaids of various types and functions. Throughout the midcourse, the RVs and penaids free fall towards their designated targets after attaining an apogee of approximately 1200 kilometers. The midcourse phase lasts approximately 1000 seconds.

The final, or terminal, phase begins when the reentry vehicles and penetration aids reach the upper limit of the sensible atmosphere at approximately 100 kilometers. Reentry into the atmosphere lasts from 30 to 100 seconds depending upon the trajectory of the RV. During reentry, the lighter, unhardened, ill-shaped penaids and missile debris are stripped away from the threat cloud by atmospheric drag, leaving only the warhead to be targeted by a defense. The final event in a missile trajectory is the detonation of the missile's warheads. The entire sequence of phases, from launch to impact, occurs approximately over a mere 30 minutes.

The trajectory described above is based upon minimal energy requirements since no defense is currently available to interrupt the missile sequence. Should ballistic missile defenses become operational, a number of options arise. At the expense of more propellant and possibly fewer warheads, the Soviets could place the missiles into depressed trajectories, thereby shortening the amount of time available to a space-based defense. As an alternative, the Soviets could place the missiles into lofted trajectories resulting in a shorter terminal phase. Conceivably, the Soviet Union would use a variety of such trajectories when launching a first strike in order to fully stress the defense.

There are no fundamental differences between ICBMs and SLBMs or IRBMs. However, because of the lesser geographic range required to travel, SLBMs and IRBMs travel

along a much shorter, depressed trajectory thereby decreasing the time between launch and impact and the targeting accuracy available. The flight time of an SLBM could be as short as 8 to 10 minutes as compared to 30 minutes for an ICBM. Additionally, the SLBMs own the important element of surprise which further stresses any proposed defense.

2. <u>Cruise Missiles</u>

Cruise missiles are, in effect, small unmanned aircraft which are preprogrammed to fly along a specific, low-level flight path to the designated target. The missiles are capable of delivering nuclear warheads with great accuracy over a range of 3000+ kilometers; however, the time from launch to impact is greater than that of ballistic missiles. Soviet cruise missiles under development are capable of being launched from air, land, sea, or subsurface platforms. Due the simplicity of flying low over the unobstructed ocean surface, the cruise missile is considered particularly threatening to naval warships and coastal areas.

IV. SDI TECHNOLOGIES

The technologies and architectures proposed for ballistic missile defense range from the simple to the sophisticated and from the exotic to the elementary. While a knowledge of these proposals is necessary to ascertain the feasibility of the effort, the concepts currently under investigation are so tentative and undefined that an attempt to compare specifics would be premature. Therefore, this section will merely familiarize the reader with the general concepts which were the genesis of the Strategic Defense Initiative.

A. MULTITIERED BMD

Numerous studies and analyses have supported the conclusion that an effective ballistic missile defense needs to be multitiered. This defense-in-depth concept stems from the consideration of several factors :

(1) A single line of defense must by necessity be highly sophisticated to provide even a modest level of effectiveness against the vast number of targets which it will face in an all-out ballistic nuclear war. Additionally, this single front would be vulnerable to countermeasures specifically developed to thwart its technology. In a multitiered system, the technology used in each tier need not be as complex in order to achieve the same level of effectiveness. The vulnerability of the defense would also be reduced. Each tier could be structured with a different type of technology so that any single method an attacker used to circumvent the defense would not equally effect each tier of the engagement.

(2) Given that some leakage can be expected from any single layer of defense, a multitiered defense can add to the uncertainty faced by the Soviet military planner. Leakage is defined as the percentage of warheads which get through a layer intact and operational. The Soviets could lessen the effectiveness of a single line of defense through sheer proliferation of missiles while still maintaining a high probability of success. However, with a multitiered BMD, the Soviet planners would face increased uncertainty as to the number of warheads that could reach their designated targets and, therefore, would also be uncertain as to the amount of retaliation they could expect.

(3) A multitiered defense may be more cost effective than a single front. A system of three defensive layers, each allowing 10% leakage, is likely to be cheaper than one layer of the same 99.9% effectiveness.

The most attractive phase to defend against is the boost phase. During this phase, the rising missile is easily targeted due the highly specific infrared (IR) signature generated by the missile as it passes through the dense atmosphere. Additionally, the booster rockets present larger, more fragile targets than do the individual reentry vehicles of later phases. Perhaps the most prevalent reason for boost phase intercept is, however, the great numerical leverage presented to the defense. For every missile killed during the boost phase, the number of objects to be handled by the remaining elements of a multitiered BMD is reduced by a factor of 10 to 100 or more.

Defense in the post-boost phase is also highly attractive although the leverage to be gained in this phase decreases rapidly with time. As the bus releases reentry vehicles and penaids, its value as a target declines. Consequently, early interception of the bus provides the highest numerical leverage. Strategic leverage may also be gained. By destroying the bus early, RVs not yet deployed may still arrive over the U.S. (due their ballistic nature) but not near their intended targets.

Further strategic leverage available from both boost and post-boost defenses stems from the fact that interception during either of these phases disrupts the highly structured attack sequence required to optimally utilize ballistic weapons. In summary, perhaps even a modest level of attrition during the early phases of a Soviet ballistic missile attack would be sufficient to destroy any confidence the Soviet Union may have towards a successful first strike.

The major disadvantage to boost and post-boost defenses is the short time available for interception. A midcourse defense would not have this disadvantage. However, midcourse

defense presents its own formidable problem--the large volume of reentry vehicles, penetration aids, and missile debris that must be acquired, tracked, and targeted within the cold reaches of space. Also, throughout the entire post-boost and midcourse phases, a search must illuminate the threat cloud with radar or laser or search for a very weak infrared signal in order to attempt to discriminate the warheads from the decoys and debris. Without an efficient discrimination, a defense would have to intercept each element of the threat cloud to insure the warheads are destroyed.

Defense in the terminal phase is also hampered by time availability but not by the need for discrimination. Reentry into the atmosphere filters out the lighter, unshaped decoys and debris in the threat cloud leaving only the armed reentry vehicles or highly sophisticated decoys which must be assumed to be armed. Additionally, air friction heats the falling RVs thereby providing a good IR signature for targeting.

The very physical structure of the described multitiered defense places a number of architectural and technological requirements on the system designer in addition to those obstacles placed by the actual weapons technologies. For example, hundreds of booster rockets rising through the atmosphere thousands of miles from U.S. territory may only be attacked from space; therefore, satellite technology is required for boost and post-boost defenses at the minimum. Midcourse defense may possibly be conducted from the ground or inside the atmosphere while terminal defenses, by definition, are endoatmospheric.

A multitiered BMD also requires an intricate battle management system in order to efficiently allocate weapons to targets throughout each phase of the attack. A primary requirement of the system would be to conduct birth-to-death

tracking of all objects posing a potential threat. The system would have to discriminate RVs from penaids, pass track and target information between defensive tiers, and assign weapons to individual targets. In addition, the functions of surveillance, acquisition, tracking, and kill assessment (SATKA) would have to be conducted within each tier. The prodigious data handling problem thus posed by multitiered BMD would require precise, high speed, large volume computing technology that may possibly also be space based.

The previous discussion should impress upon the reader that, although a multitiered ballistic missile defense poses numerous obstacles to the designer, this type of architecture does have great potential for providing an effective defense.

B. WEAPONS TECHNOLOGIES

Major advances in weapon systems technologies have occurred since ballistic missile defense was last seriously discussed in th early 1970's. The capability for satellite basing and improvements in fast, high volume computing have also become available. The potential of these new technologies to provide an effective defense resulted in the establishment of the Strategic Defense Initiative.

A driving factor in the feasibility of a BMD is the time available for target engagement. This parameter is particularly pertinent in the short boost and post-boost phases due the high numerical leverage that is possible. Consideration of this factor has directed systems designers towards high speed interceptors that can be based and/or can engage multiple targets in space. As a consequence, most of the discussion and publicity surrounding SDI has addressed the use of space-based directed energy weapons, such as lasers. It was, in fact, the concept of using this type of weapon which dubbed the program with its "Star Wars" nickname.

Directed energy weapons (DEWs) appear to be highly desirable over the previous kinetic energy weapons (KEWs) for the following reasons :

- DEWs allow target engagements to be conducted at or near the speed of light,
- DEWs provide a nonnuclear kill mechanism,
- DEWs allow for highly surgical engagements with minimal collateral damage to nontargets,
- DEWs could provide a large (possibly unlimited) multiple engagement capability, dependent on power requirements,
- DEWs have the potential for continuous worldwide threat coverage while utilizing a small number of systems due their long lethal range,
- DEWs have an inherent self defense capability.

Based on the above, the decision maker may conclude that the research effort should focus only on this new type of weapon. However, numerous tradeoffs exist which make kinetic energy weapons still a valid alternative. As an example, among the tradeoffs is the tracking and targeting criteria. A DEW must actually strike the target in order to inflict damage whereas an explosive KEW can be effective at a considerable distance. Therefore, for a directed energy weapon to destroy its target, the position of the target must be known to within a distance equal to the target's shortest dimension and the DEW must be pointed with the same accuracy. This requirement poses a serious obstacle to the use of directed energy weapons. Other tradeoffs include the potential power requirements, the capability for endoatmospheric intercept, the number of interceptors per satellite, and the degree of battle management required.

This discussion should convince the reader that research into all types of defensive weapons, architectures, and strategies must be continued in order to assess all options. For this reason, the technologies under serious study range from kinetic energy weapons, such as the hypervelocity electromagnetic rail gun, to directed energy weapons, including

lasers and particle beams. Additionally, other technologies continue to emerge for consideration and prior defensive weapons systems, originally designed only for terminal defense, are being reevaluated. The reader will be introduced to the newer technologies to assess their potential.

1. <u>High Energy Lasers</u>

The weapons technology currently receiving the most attention is the high energy laser. The word "laser" is an abbreviation of the term "light amplification by the stimulated emission of radiation." This concept involves using some source of external energy to cause the oscillation of atomic particles between energy states and thereby causing the emission of radiation. The ultimate result of the action is a stream of coherent electromagnetic waves--that is, light waves all of which have the same frequency, phase, and direction of motion. These waves are focused into a tight beam of high intensity via precise optics. The lasers under study for SDI include the chemical, excimer, free electron, and Xray lasers.

a. Laser Kill Mechanisms

Lasers output energy in basically two modes, continuous wave (CW) or pulsed. To kill a target, a laser must deposit this energy onto the target's surface. The proportion of laser energy that would be absorbed by a target depends on the frequency of radiation, the material hardness of the target, and the condition of the target's surface.

A continuous wave laser causes physical damage to a missile target by heating the outer surface of the missile until the beam burns a hole through it. Due the moderate intensities of CW lasers, this type of thermal kill requires a relatively long time on target (dwell time), probably on the order of seconds. The actual damage done would depend on the type of target (RV, bus, or booster) and

where the target was illuminated. Drilling a hole through the fuel tank could cause venting and/or ignition of the fuel leading to a loss of control in the boost phase. A rupture on the surface of the missile in flight may cause structural collapse. Disabling the fuse which triggers a nuclear warhead would prevent the warhead from exploding or possibly cause it to explode prematurely. Finally, knocking the guidance controls could cause the warheads to impact far from their designated targets.

A pulsed laser can also cause damage in a variety of ways. Repetitive, moderate intensity, short laser pulses could be aimed at the missile's electronic guidance. The abrupt heating and cooling would cause thermal shock, perhaps sufficient enough to shatter the glass and ceramic semiconductors. Probably more effective would be a single pulse of extreme intensity. The laser pulse would instantaneously vaporize a thin layer of the target's skin. generating a high impulse or shock wave that would travel through the target possibly causing mechanical failure or structural collapse. Using a single or even a small number of high intensity pulses would alleviate the dwell time problems posed by CW lasers.

b. Laser Propagation

Due their high speed of intercept, lasers can be deployed a considerable distance from their targets; however, this distance is not unlimited. The effective range of a laser is constrained by the physical principles of diffraction and attenuation.

While a laser can originally emit a perfectly formed beam of energy, the wave nature of light guarantees that the beam will eventually spread and become progressively more diffuse, even in the vacuum of space. This phenomena is known as diffraction. Diffraction limits the size of the spot to which a laser beam can be focused. The

diameter of the spot (d) grows in proportion to the wavelength (w) and target range (r) and inversely proportional to the size of the focusing mirror (D), in accordance with equation 4.1 :

$$d = 1.22\ w\ r\ /\ D \quad \text{(meters)} \qquad \text{(eqn 4.1)}$$

As the spot size increases, the energy carried by the beam is spread over a growing area and therefore the beam's destruction potential decreases.

The quality of the optics is also a factor in diffraction. Should the focusing mirror be imperfect, the spot formed will be larger than the diffraction limit; correspondingly, the energy deposited per unit area will be reduced thus making the laser a less effective weapon. Constructing a large perfect mirror presents a significant obstacle to SDI. The size of the mirror required for a given range and effectiveness depends on the wavelength of the laser, as shown in equation 4.1 . Shorter wavelengths permit the use of smaller mirrors. A possible alternative to a single large perfect mirror is the design of a large optical surface comprised of a number of small perfect mirrors combined so their positions are all aligned to within a fraction of a wavelength. Of particular note in the relationship between optics and wavelength is that, due their extremely short wavelength, Xrays penetrate matter and are absorbed. Therefore, Xrays cannot be back reflected by any type of mirror and special targeting technologies must be utilized.

Attenuation is the weakening of the intensity of light through atmospheric absorption. The attenuation of a laser beam in space is negligible; however, once atmosphere is encountered, the strength of the beam decreases rapidly. The attenuation that occurs to light energy is evidenced by

the protection that the atmosphere provides us from the harsh rays of the sun. This same shield may protect missiles in the boost phase.

The amount of attenuation which occurs to a laser beam is also dependent upon the wavelength of the beam. In short, the longer the wavelength, the less the attenuation--although gaps do exist throughout the spectrum of light energy. Therefore, the altitude to which a laser beam can penetrate the dense atmosphere varies with the type of laser. Of those under study, chemical lasers have the longest wavelength. Physicists theorize that this laser can propagate down to approximately 100 km and still have sufficient energy to injure a rocket booster. At the opposite extreme, Xrays are strongly absorbed by even the thinnest atmosphere and may therefore prove useless for endoatmospheric intercept.

One concept in the use of laser technology for strategic defense is to base the laser and its power supply on the ground. The laser beam would be sent into space where it would be refocused and targeted by an orbiting mirror. This concept therefore requires the beam to also pass through the dense inner atmosphere, thus compounding the problems of beam propagation. The most dominant factor in inner atmospheric interference is turbulence in the air. Atmospheric turbulence distorts the wavefront of the beam causing a loss in beam coherency. This phenomena is evidenced by the twinkling of stars and distant lights.

The effect of turbulence can be compensated for by a technique called adaptive optics. A primary laser beam is sent through the atmosphere while sensors measure the distortion caused to the beam. A second beam is then generated but altered to compensate for the distortion, thereby maintaining coherency. Adaptive optics are currently limited to atmosphere close to the laser source and therefore are not considered as a viable aid to space-based lasers.

c. Laser Types

The laser type currently at the highest state of maturity is the chemical laser. As implied by the name, this laser derives its energy from a chemical reaction between two chemicals at different energy states. The reaction may occur naturally or may be triggered by a small electrical discharge. The chemical combinations under most intense investigation are hydrogen-fluoride (HF) and deuterium-fluoride (DF). The tradeoff between these two combinations includes both wavelength and cost. DF laser wavelengths are longer than those produced by HF lasers and therefore travel through atmosphere more efficiently. However, deuterium is very rare and hence much more expensive as a lasing source. Other promising chemical combinations include carbon-oxygen and oxygen-iodine.

Most chemical laser research has produced devices which yield a continuous wave beam. Since chemical reactions are difficult to rapidly regulate, producing pulse lasers with chemicals may prove infeasible. The major advantage, from a military standpoint, of chemical lasers over the previous crystalline and gas-dynamic lasers is the capability for compact energy storage. Should the laser system be based in space, chemical fuels can be stored more efficiently over long periods of time than electrical power supplies.

A promising technology for generating a tunable continuous wave beam is the free electron laser. The basic physics of a free electron laser is to utilize a particle accelerator to bring a beam of electrons to a high velocity and then pass the beam through a specially tailored magnetic field. The magnetic field is formed by a linear array of magnets, called a wiggler, that alternate in polarity so that the electron beam is subjected to regular oscillations in the magnetic field strength and direction. The

oscillations of the beam cause the electrons to emit light energy. Mirrors properly placed then focus the light energy and create a laser beam. By adjusting the magnet spacing and the energy level of the electrons entering the system, the wavelength of the resulting beam can be tuned to allow system designers to optimize on atmospheric propagation and mirror sizing.

The excimer laser is a combination of the concepts of chemical and free electron lasers. Its light energy is the result of directing an electrical discharge or beam of electrons into a gas combination containing excimers. Excimer stands for "excited dimer", a molecule consisting of a pair of atoms bound together only when the molecule is in an excited state. When, as a result of electron bombardment, the molecule drops into a lower energy state, the molecule disintegrates and produces light energy. Excimer lasers can produce either continuous wave beams or high power pulses at short ultraviolet wavelengths.

The most controversial proposal for laser beam weaponry is the nuclear pumped Xray laser. Due the extremely short wavelength provided, this weapon could only be deployed in space and would be effective only after targets cleared the atmosphere. The laser consists of a small nuclear bomb at the core of bundles of fibers of lasant material. Explosion of the nuclear bomb generates Xrays which are captured by the bundled fibers and focused into a laser beam before the bundles are destroyed by the resultant nuclear blast.

The fact that an Xray laser inevitably self-destructs imposes limits on the way it can be used. Because Xrays travel at the speed of light while the resultant shock wave travels more slowly, a short laser pulse can be generated before the fibers are destroyed; however, the bundles of fibers would have to be perfectly targeted prior to

triggering the nuclear bomb. No mirrors could be used to retarget the pulse due its wavelength. On the positive side, Xray lasers could provide an instantaneous multiple target capability based on the number of fiber bundles deployed. Further, each pulse generated would be of extremely high intensity and no dwell time on target would be required. Xray lasers also would utilize a power source that can easily and efficiently be stored and generated.

2. Particle Beam Weapons

Perhaps the most exotic of the technologies proposed for strategic defense is the particle beam, a military adaptation of cathode ray tube technology. A particle beam is a stream of atomic or subatomic particles of like energy states which is generated by a high voltage electric pulse and accelerated by an electrical and/or magnetic field, thereby increasing the kinetic energy of the particles. Nature's analogy to the particle beam is a bolt of lightning. A particle beam weapon would collectively direct the atomic particles towards a target and, if the particles hit, could cause great and possibly instantaneous damage.

Particle beams interact with matter in a manner totally different than that of laser beams. Each particle that strikes the target with sufficient energy would penetrate the target and travel through it. As it penetrates, each particle loses energy by transfering that energy to electrons within the target via a series of inelastic collisions. The amount of energy the particle deposits in the target depends on the mass and energy of the particle, the nature of the target, and the distance travelled in the target. The penetration depth is inversely proportional to the density of the absorbing target material.

Given enough particles impacting with the target in a short time, the deposited energy could cause damage in a variety of ways. The kinetic energy lost by the particles

would eventually manifest itself as heat. Thermal kill could occur by ignition of the rocket fuel, detonation of the high explosive trigger of a nuclear warhead, structural collapse, or melting internal electronic guidance or critical components. Electronic "soft" kill may occur due the upset of unshielded electronics by transient radiation effects similar to those caused by nuclear explosions. Also, a sudden influx of electrons might knock out a semiconductor device's memory, rendering it either temporarily useless or permanently disabled.

Particle beam weapons are similar to laser weapons in that the destructive energy of a particle beam travels at near the speed of light and that, to cause damage, the beam must have a direct hit on target. Particle beams are also subject to diffusion by the atmosphere. Particle beams are classified as either charged or neutral.

Charged particles are those particles with either a positive or negative electrical charge and consist of electrons, protons, and positive or negative ions. Only electrically charged particles can be accelerated and aimed as a high energy beam; however, this type of beam poses significant physical problems to the weapons designer. Each particle in a beam of like charged particles is subject to mutual Coulomb repulsion by all other particles and therefore rapid radial spreading of the beam would occur. Similarly, the charged particles actively interact with atoms in the atmosphere thereby causing the beam to quickly become more diffuse. The more serious obstacle, however, is the divergence of a charged particle beam caused by the earth's geomagnetic field. Charged particles are deflected away from their original path by any magnetic field in an amount inversely proportional to the momentum of the particles and directly proportional to the strength of the magnetic field. Due the irregularities of the earth's

geomagnetic field, a charged particle beam would bend in complex and possibly unpredictable ways thus making the beam difficult to aim. The uncertainty in the amount of deflection of a charged particle beam would be proportional to the uncertainty of the strength of the geomagnetic field at any point along the beam's path.

The problem of propagating a charged particle beam through the atmosphere may possibly be solved by a technique known as hole boring. A channel in the atmosphere would be evacuated of charged particles via ionization thereby allowing the beam to travel unhindered. The evacuated channel, or hole, would be bored by either a high energy laser or by pulsing the charged particle beam such that each pulse bores a hole through which the next can travel. Via this technique, it may be possible to propagate a charged particle beam a few kilometers; however, the beam would still be subject to geomagnetic deflection. In addition, once the beam reaches the vacuum of space, it rapidly disperses due mutual particle repulsion therefore limiting a charged particle beam weapon to ground basing and endoatmospheric intercept.

The requirement for exoatmospheric intercept drives researchers to consider neutral particle beams. Since only charged particles can be accelerated and aimed via electromagnetic fields, a neutral particle beam is generated by first generating and aiming a charged particle beam and then neutralizing the charge on this beam. The most advanced neutral particle beam currently available is comprised of neutral hydrogen (H^0) atoms. A beam of negatively charged hydrogen (H^-) atoms is generated via a particle accelerator, focused and steered via a system of magnetic lenses, and then neutralized by passing the beam through a gas chamber to strip off the extra electron thus forming a stream of neutral (H^0) particles. The electron stripping can also be

accomplished by passing the beam through an externally imposed magnetic field or through a laser beam. Once a neutral particle beam hits a target, it converts back into a charged particle beam with the resulting damage as previously discussed.

In the vacuum of space, high energy neutral particle beams can travel great distances. Although the neutral particles are subject to the earth's gravitational pull, the beam travels at essentially the speed of light; therefore, the effect of gravity is negligible and the beam travels in a straight line. Once atmosphere is encountered, however, these positive qualities are lost. A neutral particle beam cannot propagate stably through even the thinnest atmosphere. The rapidly moving neutral atoms would collide with air molecules and be converted into electrically charged ions and particles which would be fanned out by the earth's geomagnetic field. For this reason, physicists theorize that neutral particle beams would be ineffective below approximately 160 km from the earth's surface.

Significant problems with both types of particle beam weapons are targeting and kill assessment. It would be difficult to ascertain the miss vector between a particle beam and the target. Therefore, the defense may have to fire blindly and repeatedly until the BMD target either explodes or tumbles out of control. Target kill would not be so readily apparent if caused by transient radiation. Alternatively, the weapon could be preprogrammed to stochastically fire a fixed number of particle pulses and then shift to the next target without positive knowledge of a kill. Another significant obstacle is space basing. The immense power required to accelerate a particle beam may possibly not be feasibly stored or generated in space. Additionally, the magnetic lenses which focus and aim the beam must themselves be carefully shielded from the geomagnetic field without degrading the energy of the beam.

3. Kinetic Energy Weapons

Kinetic energy weapons designed for ballistic missile defense have been under study within the U.S. for more than two decades. This type of weapon is advantageous to system designers since KEWs do not require the level of sophistication as do directed energy weapons. In addition, although the only U.S. kinetic energy BMD system ever deployed was dismantled in 1975, the previous defense technologies provide current researchers with a vast technological and analytical base from which to proceed.

Most previously conceived kinetic energy BMD systems utilized a nuclear kill mechanism to accomplish terminal defense from long range. However, driven by the intent of the Strategic Defense Initiative, current concepts involve using either direct impact projectiles or fragmentation warheads in order to achieve a nonnuclear kill within all ballistic phases. The two nonnuclear concepts receiving the most attention are the miniature homing vehicle (MHV) and the electromagnetic rail gun.

The miniature homing vehicle is a self propelled missile currently under development as an antisatellite (ASAT) system. The missile is carried aloft by an F15 aircraft and then uses a two stage rocket to reach low altitude orbiting satellites. Once launched, the MHV homes in on the target using a cryogenically cooled IR sensor and then damages the target via direct impact. This concept is different than the Soviet ASAT system which has a killer satellite pull up next to a target and then explode, sending thousands of pieces of shrapnel into the target's control, electronic, and power systems. As of this writing, the MHV is the most fully developed potential BMD weapon; however, whether a satisfactory defensive tier can be built around this technology remains to be demonstrated.

The hypervelocity electromagnetic rail gun is a mass accelerator, based on the idea of a open solenoid, which launches small direct impact projectiles at speeds on the order of kilometers/second. In principle, the rail gun is similar to the electric motor, which uses a magnetic field to accelerate an armature. The rail gun uses an extremely powerful magnetic field to force small masses along conducting rails at high velocity. These masses are currently inert but the possibility of launching individual homing missiles via this technology is being considered.

Numerous nonnuclear kill KE systems have been proposed for terminal defense. The proposals usually include a rocket armed with a fragmentation warhead or flechetttes. Of note is a ground-based system named SWARMJET which sprays large salvos of unguided masses at reentry vehicles during the last seconds before impact.

For a number of reasons, the driving parameter in kinetic energy weapon systems is the speed of the projectile. Primarily, the projectile must have sufficient terminal velocity to impart enough energy on the target to cause damage. The relationship between velocity and energy is shown in equation 4.2 where Vt is the terminal velocity (km/sec), M is the mass (kg) of the projectile, and E is the energy (Joules) deposited on the target. This requirement limits the effective range of KEWs travelling through the atmosphere due the loss of velocity from air friction. Further, kinetic energy kill vehicles move very slowly in comparison to directed energy beams and, consequently, the time window available for intercept within each phase is dependent on the speed of the projectile rather than the missile phasing. If boost phase intercept is considered a system requirement, this dependency may force the use of an uneconomically large number of KEW satellites. On a positive note, direct impact kills are immediate; therefore, no dwell

time is required and numerous targets can be engaged almost simultaneously.

$$E = (M/2)\,Vt^2 \quad \text{(joules)} \qquad \text{(eqn 4.2)}$$

Consideration of the speed of intercept brings up the old question of "can a bullet hit a bullet ?" Killing an extremely fast moving target via direct impact with an interceptor hampered by a significantly lesser speed capability is a difficult task. Prior experience with air defenses shows that an interceptor requires a significant advantage in speed to overcome an aircraft. However, reentry vehicles may travel over twice as fast as potential KE interceptors. The important difference is that RVs are on precise trajectories and cannot maneuver away from the interceptor. This difference makes BMD more like satellite interception than anti-aircraft warfare.

Other important factors in the use of kinetic energy weapons are the tradeoffs involved in using either guided or unguided interceptors. The immediately apparent tradeoff is cost. An interceptor capable of autonomous homing would obviously cost more than a simple unguided interceptor. Should guidance be required, a possible solution would be the use of directed homing. The carrier satellite or ground system could provide laser or RF designation of targets thereby eliminating the need for fully autonomous target detection, tracking, and homing. This configuration would reduce interceptor complexity, weight, and cost. Another tradeoff exists in the effectiveness of the projectile. In the turbulent environment following a nuclear explosion, an unguided interceptor may not be able to adhere to its predetermined course and therefore guidance may be required. In opposition, the use of guidance may constrain space-based KEWs to exoatmospheric intercept. A kinetic energy

projectile with IR sensing and homing would be subject to air friction when passing through the atmosphere. The heat generated by the air friction might either mask or blind the IR homing sensor thereby rendering the projectile ineffective.

4. Emerging Technologies

As technology advances, other weapons concepts are sure to emerge for consideration. A revisit to this subject after even a short period of time may find a currently unconceived device at the forefront.

A promising technology now being reevaluated is the microwave generator. Microwaves show great promise in that they are easily generated via conventional high explosive or nuclear devices and that they propagate through the atmosphere unattenuated at all but the most extreme output levels. A high power microwave DEW could cause degradation or damage to unshielded electronic and guidance systems by introducing spurious radiation. Even weak microwaves can upset circuitry as evidenced by the interaction between modern microwave ovens and coronary pacemakers. The effectiveness of this type of "soft" kill would be difficult to ascertain; therefore, microwaves may be used more as a harassing tactic than as a kill mechanism. Given extreme output power levels, microwaves may also be capable of hard thermal kill. In a manner similar to modern ovens, microwaves may provide a rapid heating and cooling sequence that would stress structural and functional components on the target. Another potential use of microwaves is for communications and guidance jamming.

Other potential technologies include enhanced electromagnetic pulse (EMP) weapons and antimatter beams. Research into EMP has been ongoing since the advent of nuclear weapons, both as a catastrophic result of nuclear war and as a possible offensive or defensive asset.

Antimatter beams are similar to particle beams and would cause the destruction of individual atomic particles within the target. While these advanced technologies seem to be more in the realm of science fiction than of modern alternatives, the designer and decision maker must keep an open mind for new ideas and possibilities.

C. WEAPONS DEPLOYMENT STRATEGIES

Within any weapons system, the method used in deploying the weapons is as critical as the actual weapons themselves. Key factors in the feasibility of a weapons system which depend on the deployment strategy are the overall system cost, the time available to decision makers for C^3, the amount of uncertainty posed to decision makers during the engagement, and the countermeasures available to the opponent, to name only a few. BMD system designers are faced with a set of deployment options which is as large and varied as the set of weapons technologies previously discussed. Towards providing a system level understanding of SDI, this section will define the major deployment options and discuss the tradeoffs within and between the alternatives.

1. Boost Phase On-orbit Satellites

The physical laws of nature and the political environment of the world combine to require the use of satellite technology for boost phase interception. Since Soviet ICBM silos are not within the line of sight of the U.S. or its allies and since the U.S. cannot station its defenses on or near Soviet soil, a defense which attempts boost phase interception must be based in space either before the attack or during the attack sequence. This requirement presents to the system designer an extremely complicated problem whose solution depends on a large number of highly variable parameters and political decisions. This requirement has thus caused most of the discussion, argument, and controversy within the scientific community.

The crux of the problem in on-orbit satellite basing is how many satellites are required to meet the threat. Since the satellites will be the "big ticket" items of an on-orbit boost phase defense, knowledge of the number of satellites required is paramount in determining total system cost. The required number of satellites is dependent on a variety of factors but primarily on the area to be covered and the effective range of the defensive weapon used.

The area to be covered by a boost phase satellite defensive tier is tied to the overall goal of the defensive system. If the U.S. is only concerned with the Soviet ICBM threat, then only the Soviet homeland needs to be covered. Conversely, if the U.S. is also concerned by the Soviet SLBM and IRBM threat or by any ballistic missile fired from any sector, then global coverage would be required. The effective range of a defensive satellite depends on the type of weapon utilized onboard the satellite and its operating characteristics. The effective range of a directed energy weapon is contingent on the output power density placed on the target while the effective range of a kinetic energy weapon is contingent on its projectile velocity.

The previous two parameters, coverage required and satellite weapons range, combine to drive a third parameter, the type of satellite orbit. In a simplistic review of orbital mechanics, a satellite must be placed into orbit at a velocity that is sufficiently high so that the satellite motion can offset the downward pull of gravity and therefore a stable orbit can be maintained. The altitude at which the satellite is placed determines the amount of surface area that the satellite can see; the higher the satellite, the larger the look area. The altitude also determines the period of the satellite's orbit, that length of time required for the satellite to complete one full revolution around the earth.

Satellites in a low orbit (up to approximately 1000 km in altitude) have a period of about 1.5 hours or less. Since the earth also revolves as the satellite orbits but at a different period (24 hours), a low orbiting satellite will not always be overhead the same geographic area. Rather, a low orbiting satellite will be absent from that geographic area for a specific amount of time, depending on the satellite's period and the inclination of the satellite's orbital plane relative to the equator. Therefore, to continuously cover a given geographical point, a number of low orbiting satellites in different orbits would be required and, to continuously cover the entire face of the earth, requires even more satellites.

The absenteeism problem of low orbiting satellites can be solved by placing the satellites in orbits high enough so that the period of the satellite equals the period of the earth. If the satellite is at this altitude (approximately 36000 km) and on the equatorial plane, then the satellite will remain hovered over the same geographical area. This type of orbit is called geosynchronous. Due the high altitude and large stationary look areas, the number of geosynchronous satellites required would be much less than the number of low orbiting satellites required.

The above discussion implies that for on-orbit coverage, either local or global, geosynchronous satellite basing would be a very attractive method. However, the weapons effective range must also be factored into the decision. The amount of beam dispersion that would occur to a directed energy (laser) beam travelling over 36000 km makes the use of lasers highly doubtful, even if immense mirrors and extreme power levels were utilized. Further, the time requirements imposed on kinetic energy weapons makes the use of this type of weapon in a geosynchronous orbit physically impossible. Therefore, a lower orbit is necessary and the

shorter the maximum lethal range of the weapon, the lower and more numerous the satellites must be. The problem with absenteeism then becomes significant.

Given that, due weapons range limitations, a low non-geosynchronous orbit will be required for boost phase on-orbit satellite basing, the question of how many satellites are required still remains. Fortunately for the system architects, at a sufficiently low altitude, the number of satellites required to cover only a specific geographic area is not significantly less than the number required for global coverage. Therefore, a global coverage requirement can be assumed and absenteeism is not a significant factor.

2. <u>A Model for Determining the Required Number of Weapons Platforms</u>

In an attempt to quantify the required number of defensive satellites, the following analysis will develop simple scaling rules for the number of satellites of a particular weapons type that are required to meet a given boost phase threat Additionally, the sensitivity of the model to variations in input parameters will be investigated. The initial model, developed by the Los Alamos National Laboratory, is the result of a comparison of a number of different analyses on BMD laser satellite sizing. [Ref. 5: p. 2]. The reader is reminded that the resulting numbers represent only the weapons platforms required for boost phase interception and do not include those satellites that will be necessary for surveillance, command and control, and possibly later defensive tiers.

The model will initially be developed around the use of laser beam weapons. The key parameters defining the offensive threat are :

- the number of missiles launched, M
- the amount of time the missiles are vulnerable to attack, T (secs)

- the hardness of the target, J (MJ/m^2). To destroy the missile, the power density placed on the target must exceed the missile hardness. This value is a function of the target's reflectivity and thermal protection.
- the size of the launch area, A (m^2)
- the threat rate, M / T (missiles/sec)

The key defensive parameters for a laser weapon are :

- the output power, P (Mwatts)
- the wavelength of the beam, w (m)
- the diameter of the focusing mirror, D (m)
- the range to the target, r (m)

(a) Assuming that the focusing mirror is perfect, the area, a (m^2), of the focused spot is :

$$a = pi (d / 2)^2$$

where d is given by equation 4.1 .

(b) Assuming that the laser's output power is distributed uniformly across the area of the focused spot, the average power density, Q ($Mwatts/m^2$), can be determined :

$$Q = P / a$$

(c) Assuming the laser can instantaneously slew between targets, the laser's kill rate, K (kills/sec), can be determined :

$$K = Q / J$$

Inputting terms,

$$\begin{aligned} K &= (P / a) / J \\ &= (P / pi (d / 2)^2) / J \\ &= (P / pi ((1.22 w r / D) / 2)^2) / J \\ &= (P / pi ((1.22 w r / 2 D)^2) / J \\ &= (4 D^2 P / pi (1.22 w r)^2) / J \end{aligned}$$

$$K = 4 D^2 P / pi J (1.22 w r)^2 \qquad \text{(eqn 4.3)}$$

NOTE : The above kill rate holds for a specific engagement range, r. In reality, each laser will have to engage targets over a range of r values. Therefore, the analyst should average K over all engagement ranges to determine the average kill rate, KBAR.

(d) Assume N satellites in low circular orbits providing global satellite coverage. Further assume the constellation is constructed so that the satellites are spaced at a distance of 2 R (m) apart.

(e) Given the radius of the earth, E (km), is 6370 kilometers and assuming the earth has a perfectly spherical shape, the surface area of the earth, S (m^2), is :

$$S = 4 \, pi \, E^2$$

(f) Assume R << E. Therefore, the curvature of the earth can be assumed to be negligible in the following calculations. For a satellite in low orbit, it is assumed that the subsatellite points on the earth's surface also have a 2 R spacing. Furthermore, the ground coverage area, Z (m^2), of a single satellite can be assumed to be circular. Thus :

$$Z = pi \, R^2$$

(g) Under the above assumptions, the relationship between N, E, and R is :

$$\begin{aligned} N &= S / Z \\ &= 4 \, pi \, E^2 / pi \, R^2 \\ &= (2 E / R)^2 \end{aligned}$$

Alternatively,

(h) Given a total launch area, A (m^2), assume the M threat missiles are distributed uniformly across A. If a satellite with coverage area Z is over the launch area, then

$$R = 2\ E\ /\ SQRT(N) \qquad \text{(eqn 4.4)}$$

$$E(\text{ no. missiles in } Z\ ) = Z\ (\ M\ /\ A\ )$$
$$= m$$

Further, the number of satellites, n, over the launch area at any given time is :

$$n = A\ /\ Z$$

$$n = A\ /\ pi\ R^2 \qquad \text{(eqn 4.5)}$$

(i) Assume each of the n satellites attacks the m targets within its zone. Assume the weapon's maximum lethal range is equal to R ; therefore, an average target range of R / 2 can be roughly assumed : Under these assumptions, the kill rate, k (kills/sec), of an individual satellite can be determined via equation 4.3 :

$$k = 4\ D^2\ P\ /\ pi\ J\ (1.22\ w\ (\ R\ /\ 2\ ))^2$$
$$= 16\ D^2\ P\ /\ pi\ J\ (1.22\ w\ R\ )^2$$

The total constellation kill rate, K (kills/sec), of all satellites above the launch area can also be determined :

$$K = n\ k$$
$$= (\ A\ /\ pi\ R^2\ )\ 16\ D^2\ P\ /\ pi\ J\ (1.22\ w\ R\ )^2$$
$$= 16\ A\ D^2\ P\ /\ pi^2\ J\ (\ 1.22\ w\ )^2\ R^4$$
$$= 16\ A\ D^2\ P\ /\ pi^2\ J\ (\ 1.22\ w\ )^2\ (\ 2\ E\ /\ SQRT(N)\ )^4$$
$$= 16\ A\ D^2\ P\ /\ pi^2\ J\ (\ 1.22\ w\ )^2\ (\ 16\ E^4\ /\ N^2\ )$$
$$= N^2\ A\ D^2\ P\ /\ pi^2\ J\ E^4\ (\ 1.22\ w\ )^2$$

(j) Assume the total constellation kill rate, K, is equal to the threat rate, M / T :

$$M\ /\ T = N^2\ A\ D^2\ P\ /\ pi^2\ J\ E^4\ (\ 1.22\ w\ )^2 \qquad \text{(eqn 4.6)}$$

NOTE : Equation 4.6 now encompasses all the givens, leaving only the unknown N.

(k) To determine the number of satellites required for global coverage by laser weapons, equation 4.6 is solved for N :

$$N^2\ A\ D^2\ P = M\ pi^2\ J\ E^4\ (\ 1.22\ w\ )^2\ /\ T$$

$$N^2 = M\ pi^2\ J\ E^4\ (\ 1.22\ w\ )^2\ /\ T\ A\ D^2\ P$$

$$N = (\ 1.22\ w\ pi\ E^2\ /\ D\ )\ SQRT(\ M\ J\ /\ T\ A\ P\ ) \quad \text{(eqn 4.7)}$$

Example :

To provide a rough estimate of N, the following conceptual scenario will be utilized :

Offense :

(a) a launch of 1400 ICBM missiles (from Table II),

(b) distributed over a launch area of 10 Mm^2 (roughly the land area of the Soviet Union),

(c) with a boost phase of 180 seconds (from Table IV),

(d) and a hardness of 20 kJ/cm^2 (estimate of future Soviet solid fueled ICBM booster hardness. RV's would be harder and satellites softer),

Defense :

(a) an onstation "20/10" chemical laser defensive system providing

(b) output power of 20 Mwatts (estimate of future output power available),

(c) a beam wavelength of 2.7 microns (current chemical laser wavelength),

(d) and using a focusing mirror 10 m in diameter (estimate of future technology. Largest astronomical mirror currently used is approximately 5 m in diameter).

Calculations :

$w = 2.7$ microns

$= 2.7 \times 10^{-6}$ m

$E = 6370$ km

$= 6370 \times 10^3$ m

$J = 20$ kJ/cm^2

$= 200 \times 10^6$ J/m^2

$= 200 \times 10^6$ Watt sec/m^2

$A = 10$ Mm^2

$= 10 \times 10^{12}$ m^2

$P = 20$ Mwatts

$= 20 \times 10^6$ watts

From equation 4.7, N = 117.1 ; therefore, 118 laser satellites are required for global coverage and boost phase intercept. From equation 4.4, R = 1172.8 km and from equation 4.5, 2.3 satellites will be able to see the Soviet Union at any given time.

<u>Sensitivities</u> :

(a) The driving assumption of the above analysis is that constellation kill rate (K) is equal to missile threat rate (M/T). Under this assumption, the defensive constellation was sized for full stress; that is, the Soviets may choose to fully stress any defensive system by launching all the offensive missiles in a nearly simultaneous manner. Refering to the example, 1400 missiles simultaneously launched while 2.3 satellites are above the launch area means that each satellite will have to defend against 1400 / 2.3 = approximately 609 missiles. Given a vulnerability window of 180 secs, each satellite will have to achieve a kill rate of 609 / 180 = approximately 3.4 missiles/sec. This figure appears intuitively infeasible; especially when consideration is given to time factors such as weapons slew rate and C^3/battle management requirements which may significantly reduce the window of vulnerability. Due these technology and management limitations, the system

architect may desire to adjust equation 4.7 by a constant, c ($0 < c \leq 1$, typically), to better relate threat rate to kill rate (e.g. when under full stress, satellite kill rate may be only a fraction of missile threat rate). Additionally, equation 4.7 might also be adjusted to encompass a more limited single tier goal; that is, the architecture may only require that a fraction, c, of the missiles be addressed by the boost phase defensive tier. Equation 4.7 would then become :

$$N = (1.22\ w\ pi\ E^2 / D)\ SQRT(c\ M\ J / T\ A\ P) \quad \text{(eqn 4.8)}$$

(b) As previously noted, the assumption of an average target range provides a simple point estimate of the constellation kill rate. A better estimate could be achieved by averaging the individual satellite kill rate, k, over all feasible values of target range.

(c) Under the assumptions, the significant defensive parameter interaction within equation 4.7 is between N and the output power, P. The number of satellites decreases with the square root of any output power increase. Therefore, increasing output power by a factor of four decreases the number of satellites by a factor of two.

(d) The significant offensive parameter interactions with N, under the assumptions, are as follows :

(1) The number of satellites required increases with the square root of the number of missiles launched, i.e. four times the number of missiles doubles the number of satellites required.

(2) The number of satellites required also increases with the square root of missile hardness; if missile hardness is increased by a factor of four, then twice as many satellites will be required.

(3) The vulnerability window relates to the number of satellites required by the inverse of the square root of its change. Shortening the amount of time a missile is vulnerable to one quarter of the original window doubles the number of satellites required.

(4) The size of the launch area and the number of satellites required also relate by the inverse of the square root; e.g. decreasing the size of the launch area by a factor of four requires twice as many satellites to be used. This relationship may not initially seem correct to the reader. However, a driving consideration in constellation sizing is the density of the missiles to be faced; therefore, by placing their missiles in a small geographic area, the Soviets force the U.S. to place more satellites overhead to meet the increased density. Due the absentee problem of low orbits, this increase must occur throughout the global constellation.

The above model was adapted by the author for the utilization of kinetic energy weapons. The key defensive parameter is the velocity, V (m/sec), of the rocket or rocket projectile.

(a) The velocity of the projectile and the vulnerability window determine the maximum range of the weapon, Rmax (m) :

$$Rmax = T\ V$$

(b) Setting Rmax equal to the half-swath width of the satellite, equation 4.4 can be used to determine the total number of satellites required for global coverage :

$$N = (\ 2\ E\ /\ Rmax\ )^2$$

(c) Equation 4.5 determines the number of satellites over the launch area :

$$n = A\ /\ pi\ Rmax^2$$

(d) The kill rate required by each satellite can be calculated :

$$k = (M / n) / T$$
$$= M / n T$$

(e) Assuming that each KE interceptor has the same probability of kill (Pk) associated to it and that the shots are independent, then the number of shots required for an individual missile kill, S, is a geometric random variable with a mean of $(1 / Pk)$ and a variance of $(1 - Pk) / Pk^2$.

(f) Each satellite engages (M / n) missiles. Assume this value is deterministic and, therefore, has no variance in the following calculations.

(g) The number of interceptors, i, required aboard each satellite can be quantified as follows :

$$i = (M / n) S$$

$$E(i) = E((M / n) S)$$
$$= (M / n) E(S)$$
$$= (M / n) (1 / Pk)$$
$$= M / n Pk$$

$$VAR(i) = VAR((M / n) S)$$
$$= (M / n)^2 Var(S)$$
$$= (M / n)^2 ((1 - Pk) / Pk^2)$$

$$SD(i) = (M / n) SQRT(1 - Pk) / Pk$$

(h) The total number of interceptors, I, required for global boost phase interception can also be quantified :

$$I = N i$$

$$E(I) = E(N i)$$
$$= N E(i)$$
$$= N M / n Pk$$

$$VAR(I) = VAR(N\ i)$$
$$= N^2\ Var(i)$$
$$= (N\ M / n)^2\ ((1 - Pk) / Pk^2)$$

$$SD(I) = (N\ M / n)\ SQRT(1 - Pk) / Pk$$

<u>Example</u> :

The parameters proposed for the previous example will again be utilized. Additionally, a projectile velocity of 5 km/sec and a Pk of .9 will be assumed.

<u>Calculations</u> :

$$V = 5 \text{ km/sec}$$
$$= 5 \times 10^3 \text{ m/sec}$$

$$Rmax = 9 \times 10^5 \text{ m}$$

N = 200.37 satellites
= 201 satellites total

n = 3.93 satellites over the launch area

k = 1.98 kills/sec

E(i) = 395.8 interceptors/satellite
= 396 interceptors/satellite

SD(i) = 125.2 interceptors/satellite
= 125 interceptors/satellite

E(I) = 79,596 interceptors total

SD(I) = 25,125 interceptors

Therefore, 201 satellites each carrying 396 interceptors would be the expected requirement for global, boost phase defense.

Sensitivities :

(a) The expected value results of i and I in the above analysis would still hold if the number of targets is itself a random variable with mean (M / n). This is because i and I would now be random sums of random variables. The variance and standard deviation would not be the same but rather would have to capture the variability in the number of targets.

(b) Although this analysis did not specifically address the relationship between kill rate and threat rate, the resultant kill rate required under full stress (k = 1.98 kills/sec) does not appear unattainable. Further, the significant problem of target dwell is not present in this scenario; however, missile kill assessment becomes much more important.

(c) The significant defensive parameter interactions, under the assumptions, are :

(1) Maximum range increases proportionally with velocity; further, the total number of satellites required and the number of satellites over the launch area both vary with the inverse of the square of the factor of increase. Therefore, doubling the projectile velocity doubles the maximum range and decreases the number of satellites by a factor of four. Note, however, that the expected total number of interceptors required, I, is a function of M, A, and Pk, but not Rmax.

(2) As the probability of kill decreases, both the total required number of interceptors and the required number of interceptors per satellite increase.

(d) Under the assumptions, the significant offensive parameter interactions are with the window of vulnerability, T. Rmax increases proportionally with the vulnerability window; therefore, similar to changes in velocity, as T doubles, Rmax doubles and both N and n decrease by a factor of four.

Adapting the model for neutral particle beams weapons is much more difficult due the current uncertainties in the effectiveness of a particle beam kill mechanism. Additionally, neutral particles can propagate in space over great distances at essentially the speed of light with little degradation in beam quality; therefore, a neutral particle beam weapon can conceivably be deployed geosynchronously. If so, as few as two satellites could be required for global coverage. For arguments sake, however, assume that for effective C^3/battle management the satellites are placed into low orbit at approximately 1000 km altitude. Since neutral particle beams travel in a straight line, at this altitude the line of sight distance to the horizon is approximately 3500 km and, therefore, the half-swath width (R) is approximately 3350 km. Assuming an instantaneous slew and kill, equation 4.4 can be used to roughly determine the required number of satellites :

$$N = (2 E / R)^2$$
$$= 14.46$$
$$= 15 \text{ satellites}$$

As previously noted, the number of satellites required for each type of weapon includes only weapons platforms and not C^3, battle management, or surveillance satellites. Consideration should also be given to anti-satellite satellites (ASATs) and defense-of-satellite satellites (DSATs). Of additional note is the fact that no redundancy was factored into the calculations. For survivability, it may be desirable to use several layers of satellite redundancy or to use more, less utile satellites to form a single reliable layer.

3. Other Satellite Deployment Options

The large numbers of satellites required and their sensitivities pose monumental problems to the system archi-

tect. Another significant problem is the requirement of power storage. The technologies previously discussed, with the exception of the Xray laser, all require huge amounts of chemical fuels and/or immense levels of electrical power which must be instantaneously available. Further, the power sources must be protected against attack. These problems cause system designers to consider ground basing the principle components of the defensive system.

One method under consideration for laser weapons is to base only the target sensors and aiming mirrors in space while basing a number of extremely powerful lasers and their companion power supplies safely on the ground. Under this scenario, two levels of orbiting mirrors would be required. The laser system would first direct the beam to a large mirror in a high, possibly geosynchronous, orbit in order to carry the beam around the curvature of the earth. The beam would then be redirected to smaller mirrors in low orbit and then focused onto individual targets.

This method presents several obstacles to the system architect. The fragile relay and aiming mirrors would be without the inherent protection of an on-orbit weapons system and would be extremely vulnerable to ASAT technologies; therefore, some fashion of defense would be required. Providing this defense may prove to be as costly as defending on-orbit power sources. Perhaps more significant is the tradeoff in the amount of power required. A ground based laser beam, under this scenario, would have to travel many times the range required of an on-station laser in order to reach the target. Further, during its travel the beam would pass through the atmosphere and be refocused by the space mirrors. The large increase in power required to offset losses via attenuation and reflection could drive system cost far above that of a space based power source. Other concerns include the uncertainties as to the effect of

weather on propagating the beam into space and the ability to provide global coverage when ground basing the system on U.S. or friendly soil.

Another ground basing method under consideration is the "pop-up" Xray laser. The potentially small size and light weight of this type of kill mechanism may make it possible to deploy Xray laser satellites on the ground, launching them into space only upon indication of a missile launch. This scenario would resolve the concern of having nuclear weapons continually orbiting overhead and could conceivably significantly reduce the number of laser platforms required, dependent on the ground deployment strategy.

The driving parameter behind the pop-up method is the amount of time available to the laser to fire its pulse. Due the earth's curvature, the laser must rise to a high altitude before firing in order to achieve a direct line of sight to the target. Indication and confirmation of a launch threat, C^3, and weapons deployment must all occur before missile busing is concluded; otherwise, the significant leverage of boost phase interception is lost.

The time factor involved requires the ground based satellites be deployed as near as possible to the missile launch area. When addressing the Soviet ICBM threat, this means the satellites must be ground deployed near the Soviet borders; therefore, either within allied territory or onboard submarines lingering off the Soviet coast. Basing additional nuclear weapons in allied countries may prove politically infeasible. Basing the weapons at sea may be more feasible; however, submarine basing presents its own formidable set of problems. Unless the United States is willing to give up its current SLBM capabilities, a new fleet of missile submarines will be required. Additionally, a new fleet of surface ships to support and protect the submarine fleet would also be necessary. Submarine basing of

a defensive system that would be instantaneously needed may further require decentralization and restructuring of present nuclear command authority. Due the short timeline available for C^3, each submarine commander may have to decide if and when to deploy the pop-up system for the system to effectively meet a boost phase threat.

4. Post-Boost / Midcourse Strategies

The use of both space based and ground based weapons technologies is envisioned for the middle stages of a multi-tiered ballistic missile defense. While the satellites used for boost phase defense will have some utility within the post-boost and midcourse phases, other layers of satellites of differing types of technology are being considered. These additional layers would provide a level of satellite redundancy and therefore reliability. The layers would further negate the possibility of the system being countered by a single countermeasure targeted against a specific technology.

The ground based component could consist of either directed energy weapons, pop-up systems, or long range kinetic energy weapons. An interesting concept under discussion for use with the ground based components is that of an airborne adjunct, a long endurance aircraft that would be placed into position upon warning of an impending attack. This platform would be equipped with a variety of sensors and communications systems and would be used as a battle manager in the late midcourse and early terminal phases.

5. Terminal Defense

The deployment strategy of terminal defenses, as well as the ultimate cost, again depends on the goal of the defense. The system designer is concerned with defending two types of targets - military value and social value. Each target type allows for a different defensive strategy. The goal of the defense tasks the system designer with

protecting one type of target or the other or, quite possibly, both; thus, the designer must tailor a strategy to meet the overall system goal.

Military value targets are considered as hard, point targets such as ICBM silos. An effective defense of military value targets provides the ability to launch a retaliatory strike. The amount of retaliatory force available depends on the type of defensive strategy used. First consider the case where no defense is available and all incoming RVs are targeted against hardened ICBM silos. Given a RV can disable a missile silo with probability p, the silo can launch its missile in retaliation with probability $(1 - p)$. The value of p is a function of the silo's hardness, the RV's accuracy, and the warhead's megatonnage. If r independent attacks occur on the silo, then the silo will survive all the attacks with probability $(1 - p)^r$. Assume there are L missile silos. If the attacker uniformly targets R RVs across all L silos (nonpreferential attack), then the average number of RVs per silo is $r = R / L$. Under this scenario, the expected number of surviving retaliatory missiles (S) can be determined via equation 4.9. Therefore, the number of missiles available for a retaliatory strike is driven, in the short term, by the number of RVs that are launched [Ref. 6: p. 2]. As a numerical example, the U.S. currently has approximately $L = 1000$ silos and, from Table II, approximately 1000 to 10000 Soviet ICBM and SLBM RVs can be launched. Assume $p = 0.5$. From equation 4.9, Soviet attacks with $r = 1$, 5, or 10 RVs per silo provide approximately 500, 31, or 1 expected surviving missiles, respectively.

$$S = L (1 - p)^r \qquad \text{(eqn 4.9)}$$

The effectiveness of a retaliatory strike with the S surviving missiles depends on the retaliatory missiles' own p values and on the possibility that the attacking force has its own defense against such an effort. The force being attacked can attempt to increase the number of surviving missiles by defending its silos. This defensive strategy can be either preferential or nonpreferential and is driven, in the form of a two person game, by both sides' knowledge of their opponent's weapons stockpile level, weapons effectiveness, and targeting strategy.

Nonpreferential defense simply allots the defensive capability uniformly across all silos; therefore, given the defense has I interceptors available, a nonpreferential defense would allot (I / L) interceptors to each silo. This type of defense might be considered if all the silos are of equal value and a nonpreferential attack is assumed. However, in this instance, nonpreferential defense provides little leverage to the defending force unless the number of available interceptors is equal to or greater than the number of incoming reentry vehicles. Continuing the previous example, assume I = 3000 interceptors are available and are deployed nonpreferentially. For simplicity, further assume the interceptors have a probability of kill of 1. Therefore, R = 1000, 5000, and 10000 drops to R = 0, 2000, and 7000 and, from equation 4.9, Soviet attacks with r = 0, 2, and 7 RVs per silo provide approximately 1000, 250, and 8 expected surviving missiles, respectively. The nonpreferentially attacking force can negate a nonpreferential defense by simply using more RVs than the number of interceptors available to the defense, should this value be known.

Preferential defense can present a more attractive option. A preferential defensive strategy protects only a subset of the targets with all the defenses available, leaving the undefended silos to attract a large percentage

of the incoming RVs. The value of this strategy is predicated by not allowing the offense to know which silos are defended or at what level. Assuming the attacker does not know the protection level provided to any given silo, a possible offensive strategy would be to again nonpreferentially allot (R / L) RVs per silo. Further assuming this offensive strategy is known to the defense, the defense can now protect I / (R / L) = I L / R silos completely. As long as I L >> R, the defense has gained significant leverage [Ref. 6: p. 3].

To illustrate, assume the attacker desires to disable 75 % of the missile silos in the hopes that the defense cannot launch an effective retaliatory effort with the remaining 25 % of the silos. Further assume the attacker knows the number of interceptors available to the defense but not which of the equally valued silos are defended. Under this scenario and continuing with the previous example (p = .5), the two defensive strategies can be compared on a cost basis by the number of RVs required by the offense for the terminal phase.

(a) Under nonpreferential offensive and defensive strategies, the offense would initially exhaust the defense's stockpile of interceptors and then utilize whatever number of additional RVs per silo that the attacker expected to be required to meet the offensive goal. Since the number of additional RVs required would actually follow a binomial distribution, this scenario assumes the attacker is satisfied with a mean level of disabled silos of .75 L. With independent shots, to achieve a probability of kill of .75 two RVs would have to be targeted at each silo after the interceptors have been exhausted. Therefore, the expected cost to the offense per silo would be :

$$
\begin{aligned}
R / L &= (I / L) + 2 \\
&= (3000 / 1000) + 2
\end{aligned}
$$

$$= 5 \quad RVs/silo$$

The expected overall cost to the offense in terminal phase RVs would then be :

$$(1000 \text{ silos})\ 5 \text{ RVs/silo} = 5000 \text{ RVs}$$

(b) In comparison, a nonpreferential attack on preferentially defended silos could cost the offense much more. Given that the number of RVs to be faced in the terminal phase is known, the defense could preferentially allocate R / L interceptors on each of I L / R silos to maximize the number of silos fully defended. The expected number of silos to survive the attack would then be :

$$E(\text{ survivors }) = (IL/R) + (L - (IL/R))\,(1 - p)^{R/L}$$

The offense must set R large enough to reduce the expected number of surviving silos to .25 L. So,

$$(IL/R) + (L - (IL/R))\,(1 - p)^{R/L} = .25\ L$$
$$(3000(1000)/R) + (1000 - (3000(1000)/R))\,(.5)^{R/1000} = 250$$
$$(3000000/R) + (1000 - (3000000/R))\,(.5)^{R/1000} = 250$$

The R satisfying this equation is approximately 12009, which provides 12009 / 1000 = 12.009 RVs/silo. If fractional RVs are not allowed, the offense would require 13 RVs/silo for a total of 13000 RVs. For an R of 13000, the expected number of surviving silos is 230.86 .

To summarize this limited scenario, a preferential defensive strategy can clearly provide significant leverage (13000/5000 = 2.6) to the defense over a nonpreferential strategy when faced with a nonpreferential attack. It can be shown that, for fixed silo and reentry vehicle levels and a fixed probability of silo kill, a preferential defense can be found that is always at least as good as nonpreferential defense when faced with a uniform, nonpreferential attack.

(a) Define $P(I)$ as the expected number of surviving silos under preferential defense and uniform attack as a function of I :

$$P(I) = (IL/R) + (L - (IL/R))\,(1 - p)^{R/L}$$

(b) Define $NP(I)$ as the expected number of surviving silos under nonpreferential defense and uniform attack as a function of I :

$$NP(I) = L(1 - p)^{(R-I)/L}$$

(c) It can be shown that $P(I)$ is greater than or equal to $NP(I)$ for all values of I between 0 and R. Note that, since the interceptor probability of kill is assumed to be 1, the case of $I > R$ constitutes a perfect defense.

(d) Significant relationships :

(1) $P(I)$ is linear in I.
(2) $NP(I)$ is convex in I.
(3) $P(0) = NP(0)$
$P(R) = NP(R)$

(e) Therefore, for z ranging from 0 to 1,

$$NP(\, z\,0 + (1 - z)\,R\,) \leq z\,NP(0) + (1 - z)\,NP(R)$$

(from (2) above and the definition of a convex function)

$$\leq z\,P(0) + (1 - z)\,P(R)$$

(from (3) above)

$$\leq P(\, z\,0 + (1 - z)\,R\,)$$

(from (1) above and the definition of a linear function)

(f) Letting $I = z\,0 + (1 - z)\,R$ gives the result of $P(I) \geq NP(I)$.

NOTES :

(a) It is not surprising that $P(I) \geq NP(I)$ since the state of knowledge is different in either case. The preferential defense considered uses the fact that R is known while the nonpreferential defense does not.

(b) There are numerous other scenarios where preferential defense could perform worse than nonpreferential defense. For example, using all the interceptors to defend one silo could be a particularly bad preferential defense.

(c) The offense can degrade the leverage of preferential defense by adopting a "shoot-look-shoot" tactic where the attack is launched in two waves. The first wave is used to discover which silos are being protected while the second wave is used to concentrate fire onto these defended targets. However, this tactic increases risk to the offense since it may be possible for a retaliatory strike to be launched between the offensive waves.

(d) The above notes point out the fact that terminal defense is really a complex two person game and should be analyzed as such. Much effort has already been conducted in this area [Ref. 7].

The offense, of course, is not limited to nonpreferential attack. Alternatively, the offense could choose to preferentially attack only a fraction of the silos, at a high probability of kill, while assuming the reduced number of missiles in the remaining silos could not launch an effective retaliatory effort. Numerous additional scenarios can be defined encompassing variations of offensive and defensive preferential and nonpreferential strategies at various weapons levels and states of knowledge [Ref. 7]. These scenarios are not as easily quantified as the previous example due the intricacies of a two person rational opponent game. In any of the conflict variations, however, the key to an effective defense of military value targets is not allowing the attacking force to know which silos are being protected or at what level. Thus the attacker is forced to heavily attack at increased cost to achieve his goal.

The concept of a passive preferential defense has been recently considered for use with the United States' MX ICBM missile system. Instead of actively defending missile

silos, the strategy would be to deceptively base the missiles in a large number of hardened silos, analogous to the old shell game, thereby causing the attacker to futilely expend a large number of RVs on empty missile silos. This concept is known as the multiple protective shelter (MPS) or "racetrack" strategy.

Preferential defense would not be a politically feasible option for defending social value targets. Social value targets are soft, area targets such as large cities. Grassroots logic would not allow one city to be defended while another is sacrificed; therefore, nonpreferential defense is required and the leverage shifts back to the offense. For example, an attacker uses R RVs to attack C cities protected by I interceptors. Without an extremely high level of civil defense, the attacker's probability of kill (p) rises to 1. The attacker now has the option of using only $r = (I / C) + 1$ RVs to attack each of (R / r) cities, thereby providing him with the same leverage in preferential attack of social value targets as the defense has in preferential defense of military value targets. To destroy all C cities, the attackers minimum cost in RVs (under the assumptions) is only $R = I + C$.

Another driving parameter in the defense of military value and social value targets is the amount of time available to the terminal defense. Hard, point targets must be attacked with high accuracy via groundburst or low airburst weapons. This allows the defense to launch interceptors at close range under short timelines. In contrast, soft area targets can be attacked with much less accuracy and with a high airburst. Therefore, the defense would have to commit its interceptors much earlier with much less time for battle management. As a direct result, many more interceptors would probably be needed to insure an effective defense.

The combination of strategic leverage and time requirements indicate that social value defense is a different and much more difficult task than military value defense. Determining the mix of targets to be defended, both military and social value, is a complex, political decision upon which rests the ultimate effectiveness and cost of any ballistic missile defense.

V. HOW MUCH WILL IT COST ?

In order to determine the cost effectiveness of deploying a ballistic missile defense, the decision maker must first have a reasonable estimate of the life cycle costs of the system. Unfortunately, given the immaturity of the technologies and architectures proposed and due the lack of a clearly defined goal, reliable estimates of these costs cannot be presently made. This section will attempt, however, to provide a few broad brush indicators of the major cost areas and define rough parametric cost estimating relationships (CERs) based on proposed technological capabilities.

The present SDI program thrust is to facilitate a decision in the early 1990's as to whether BMD is feasible and, if so, how the defense should be constructed. This research and development effort was divided into five major cost elements and budgeted through 1989 at a cost of $ 25 billion, as seen in Table V . Note that this sum is merely a down payment on the defensive system, which itself can be expected to cost at least tens of billions of dollars more.

Actual costs, of course, cannot be determined until specific systems are selected. Nonetheless, various groups have tried to establish cost ranges for developing a BMD system based on analogy to past U. S. large scale developmental efforts such as the Space Shuttle. A committee of Soviet scientists determined the overall development cost of a single layer space based BMD to be between $ 140 billion and $ 550 billion [Ref. 8: p. 23]. This estimate essentially agreed with DoD projections, reported to Congress in January 1982, which placed the cost of a single layer space based BMD at $ 100 billion if the system goal was to merely limit losses during a nuclear strike to $ 500 billion if the

TABLE V

DOD BALLISTIC MISSILE DEFENSE PROGRAM FUNDING

Funding levels in millions of 1984 dollars:

	FY84	FY85	FY86	FY87	FY88	FY89
SATKA	366.5	721.0	1500.0	1900.0	2700.0	3300.0
DEWs	322.5	489.0	1000.0	1200.0	1400.0	1400.0
KEWs	195.8	356.0	870.3	1300.0	1500.0	1700.0
ORSA	82.7	99.0	137.5	227.0	260.1	288.4
Support	23.5	112.0	270.8	321.9	453.0	666.7
Totals	991.0	1777.0	3778.6	4948.9	6313.1	7355.1

Grand Total 25163.7

NOTES :

a. Source: Aviation Week and Space Technology , 23 January 1984.

system goal was to provide a "perfect" defense [Ref. 8: p. 23]. Another analysis by the Soviets states that "western estimates putting the cost of a multilayer space antimissile system at $ 1.5 or $ 2 trillion appear to be justified." [Ref. 9]

It may become possible to parametrically estimate some areas of life cycle cost. For example, a rough parametric estimate of a space based system's deployment cost can be determined if the weapon's fuel requirements are known. Considering first laser weapons, roughly 1 kg of laser fuel (e.g. H_2F_2) will yield .5 MJ of laser energy [Ref. 10: p. 101]. Utilizing the assumptions and findings of the previous example on satellite requirements, the weight of the fuel required in orbit can be determined :

20 MWatts = 20 MJ/sec

20 MJ/sec (1 kg / .5 MJ) = 40 kg/sec

40 kg/sec (180 sec) = 7200 kg

7200 kg (2.2 lb/kg) / (2000 lb/ton) = 7.92 tons/sat

= 8 tons/sat

8 tons/sat (118 sats) = 944 tons of fuel required

Assuming the current Space Shuttle will be used to place the satellites in orbit, the cost of lifting one ton of payload into orbit is approximately $ 3 million [Ref. 10: p. 101]. This cost would vary with the type of orbit and may significantly decrease as the number of launches required increases; however, due a lack of system definition, $ 3 million/ton will be used.

944 tons ($ 3 million/ton) = $ 2832 million

The total weight of the satellite would reasonably be at least twice the weight of the fuel. Therefore, the system deployment cost can be roughly estimated at 2 times $ 2832 million or $ 5.664 billion per satellite layer. The reader must realize that this estimate is also subject to the assumptions and sensitivities of the model previously discussed.

Similarly, a rough estimate based on fuel requirements can also be made for kinetic energy interceptor rockets. Assuming a 5 kg mass warhead, fuel weighing approximately 9 times this mass is required to bring the warhead to a velocity of 5 km/sec [Ref. 11: p. 35]. Therefore, each interceptor would weigh approximately 50 kg. The system deployment cost can now be estimated :

50 kg (80000 interceptors) = 4×10^6 kg

4×10^6 kg (2.2 lb/kg) / (2000 lb/ton) = 4400 tons

4400 tons ($ 3 million/ton) = $ 13.2 billion

The weight of the satellite launch platforms could again be reasonably guessed to be twice the weight of the

interceptors; therefore, the system deployment cost can be roughly estimated at $ 26.4 billion. Once more, this value is subject to the assumptions and sensitivities of the previous model. Both of the above cost estimates would climb rapidly if the mirrors were imperfect, the kill rate did not meet the threat rate, redundancy was desired, etc.

As indicated in Table V , a number of other developmental efforts will be required in addition to developing weapons technologies. The intricate battle management necessitated by a multilevel system will require advances in high speed, large volume computing technologies, which may possibly be based in space. The immense amounts of energy that would be required by a DEW system under full stress could not be stored for instantaneous discharge by any presently known technology; therefore, special multi-megawatt power plants would have to be developed. The requirement for rapidly (and cheaply) lifting large amounts of weight into space may call for an improved lift capability. Based on current Space Shuttle operations, it would take several years to establish an operational system in space. Consequently, either Shuttle capabilities and scheduling would have to be increased or a new heavy lift launch vehicle (HLLV) would have to be developed to support rapid system deployment. Each of the above efforts will have a significant impact on the ultimate cost and cost effectiveness of the SDI program.

VI. BMD COUNTERMEASURES

The history of warfare in general indicates that a rational opponent will respond to any new weapons system by attempting to develop countermeasures, either offensive or defensive and at the lowest level of technology necessary, which will restore the opponent's ability to inflict damage to previously planned levels. In the case of multitiered BMD, the range and variety of responses available to the Soviets is so broad that no one can state with any certainty which of the more plausible countermeasures the Soviet Union might decide to employ. It is this uncertainty as to the Soviet response that drives much of the uncertainty as to the ultimate feasibility of ballistic missile defense.

In a classical Catch-22 situation, the uncertainty of the Soviet response grows, in part, from the uncertainty of the United States' ultimate goal and eventual architecture for BMD. To reduce these uncertainties, it is therefore essential to consider possible countermeasures to the various potential technologies in numerous possible architectures in order to further define the valid options for an effective defense. This can be considered as a winnowing process--the goals of SDI drive its potential technologies while a study of the possible countermeasures filters the technologies into feasible architectures. Further, an analysis of the impact on a proposed BMD architecture by an improved (via countermeasures) offense should also be accompanied by an analysis of the cost required to improve the defense to such a level that it cannot be effectively overcome.

While no precise, indepth analyses can be presently conducted due the lack of goal definition, countermeasures can be identified and simple heuristic estimates of their

cost, to both the offense and defense, can be determined. This is not to say that the level of uncertainty will be significantly reduced or that a particular architecture will be shown to be optimal. Because BMD is a game played against a hostile opponent rather than an optimization problem in a controlled environment, a great deal of uncertainty will always remain. Analysis can however provide the decision maker with an idea of the tradeoffs, both in cost and uncertainty, that exist when a particular countermeasure is used against a particular technology or architecture.

One of the fundamental criteria of the defensive system is that it must be cost effective at the margin. That is, to remain effective, the cost of an incremental increase in defensive capability must be less than that of the increase in offensive capability that spurred the change. If the defense is cost effective, then there is no incentive to the offense to increase its capability to attempt to overcome the defense. Otherwise, a proliferation of countermeasures and additional offensive weapons would be encouraged instead of a stabilization or possibly a reduction in offensive forces. The reader should note that this criterion also holds for the offense. If the offense cannot cheaply circumvent the defense, it may be pressured to itself change from an offensive to a defensive posture. However, if countermeasures were cheaper, then the offense could be built faster and on a scale larger than the planned defense. The current arms race would then continue.

As previously mentioned, the cost to the defense of a particular countermeasure can be considered to be the cost required to improve the defense so that planned effectiveness levels are met. The cost to the offense of a particular countermeasure is more difficult to determine. Each possible offensive response involves a number of tradeoffs. Countermeasures compete with other military programs for

available resources; therefore, a net reduction in offensive capability may result. Countermeasures also compete among themselves. A countermeasure taken against a particular defensive technology may make it more difficult to use countermeasures against other defensive components. For example, hardening the booster rockets against DEWs reduces the payload available for additional warheads or penetration aids.

Towards determining the tradeoffs in BMD driven by countermeasures, a number of different offensive responses will be identified and analyzed. These responses can be divided into three major categories : countermeasures of preemptive attack, countermeasures of offensive proliferation, and countermeasures of defense degradation. The defined countermeasures should be considered as merely a representative set of all the different responses available to the Soviets. Nonetheless, this set can be used to judge and assist in the design of any proposed architecture.

A. PREEMPTIVE ATTACK

Once the United States commits itself to deploying a ballistic missile defense in space, the Soviet Union will inevitably begin to seek out methods to overcome the defense. The most obvious way for the Soviets to achieve their goal is to simply destroy or incapacitate the defense prior to launching their offensive missiles. This type of decapitation attack can be accomplished by using any of a variety of antisatellite (ASAT) devices and tactics.

Defense suppression via the use of ASATs provides significant numerical and cost leverage favorable to the offense. Using the previous model of laser weapons platforms as an example, each boost phase defensive satellite destroyed or incapacitated over the Soviet Union prior to launch allows 609 missiles to deliver their payload to the next phase. This leverage could be even more favorable if

the offense incapacitates sensor or battle management satellites. Due the significant leverage of defense suppression, it therefore becomes paramount to an effective defense that the critical components, both ground and space based, be made survivable.

Survivability is also a concern for other reasons in addition to leverage. Current satellites are extremely vulnerable to ASATs since they are soft targets in completely predictable orbits. Future defensive satellites must be made reasonably invulnerable against an ASAT effort; otherwise, the vulnerable defense would become a tempting target during any period of conflict and could tend to intensify low level conflicts. Therefore, without a sufficient level of survivability, space based BMD could decrease rather than enhance stability.

An offensive ASAT effort will always have the advantage over any effort to protect the defensive satellites for two primary reasons. The offense does not have to attack all the defensive satellites but merely has to cut a "hole" or launch window into the defensive architecture. Further, the offense can pick the time and sequence of the attack. A pertinent question is "When will the ASATs strike ?" The Soviets could even choose not to wait until the defensive system is fully deployed but rather to attack during system assembly when the satellites are most vulnerable. Since a Soviet decision to fight today rather than face possible inferiority tomorrow is not totally implausible, this factor will make the transition period especially tense.

The only benefit the United States would receive from a Soviet ASAT strike attempt is the indication of an imminent Soviet first strike. The U.S. may therefore choose to establish and publicly declare a policy of "launch upon attack" whereas any Soviet ASAT attack on the defense will result in the U.S. launch of retaliatory missiles. Note, however,

that this type of retaliatory policy is counter to the stated goal of the Strategic Defense Initiative.

1. Offensive ASAT Options

The large number of antisatellite devices and tactics available to the Soviets can be classified into five major groups--nonnuclear direct ascent, nuclear direct ascent, ground based DEWs, space based DEWs, and space mines. It is conceivable that, just as the U.S. would use a variety of defensive technologies so that no single countermeasure would suffice, the Soviet Union would also use a variety of ASAT devices and tactics from these groups so that no single counter-countermeasure could negate the Soviet effort.

The only type of ASAT technology currently being developed by either party is nonnuclear direct ascent. The Soviet Union has a demonstrated ASAT capability based on their GALOSH missiles. The missile transits from the earth to a position close to the target satellite and then explodes on command, sending debris hurtling into the target. Nonnuclear direct ascent kills do not have to be as precise nor as obvious to the defense. A simpler measure would be to place a cloud of steel pellets into the same orbit as the target satellite but in the opposite direction. The relative velocity between the two bodies would be about 16 km/sec which is 8 times faster than modern armor piercing projectiles. If the satellite is impacted, a single one ounce pellet of steel could penetrate approximately 15 cm (6 in) of steel plate or further if properly shaped [Ref. 12]. Nonnuclear direct ascent ASATs against laser weapons can be made simper still. Since the effectiveness of the laser depends upon the precision of its targeting mirror, merely degrading this surface would severely constrain the weapon. Therefore, a possible ASAT tactic would be to place a load of fine, unshaped particles in the

path of the orbiting satellite which could pit the mirror thereby rendering the weapon ineffective.

Nuclear direct ascent ASAT tactics would be more likely to be used to degrade the entire BMD system rather than kill individual satellites. Electromagnetic pulse (EMP) is particularly severe in space and a single multimegaton nuclear explosion above the atmosphere would blanket a large area of the earth with high EMP levels. This action could produce damaging surges in sensor, battle management, and communications electronics. Precursor nuclear salvos within the atmosphere could produce atmospheric turbulence to such a degree that a defensive architecture that depended on a ground based laser would be crippled. In addition, the resultant radiation from these airbursts would degrade communications between defensive satellites and possibly blackout targeting and tracking radars on the ground. The immense levels of IR radiation produced by a nuclear blast in the atmosphere may also be sufficient to blind IR optical sensors, both ground and space based.

Should the Soviet Union acquire or develop directed energy weapons technologies of the same magnitude and quality as those proposed by the U.S. for BMD, it becomes probable that the Soviets would use this technology to attempt to regain their present status. Ground based lasers of extremely high power could be used to destroy space based defensive assets or, at least, bathe the satellites' optical sensors with blinding IR radiation. If the Soviets field their own DEW satellites, an ASAT "space war" could develop between the two systems. Since a DEW that can rapidly kill hardened reentry vehicles could surely be used against a satellite in a known orbit, this war could be fought and decided in a matter of seconds.

A possible ASAT tactic that generates a great deal of concern for the defense is the use of space mines. A

space mine would be a coorbiting satellite launched in peacetime that would remain within its lethal range of a defensive satellite. The satellite would be detonated at will via ground command at the onset of a first strike, disabling the defensive satellite by either nuclear or nonnuclear means. The satellite would also be salvage fused; that is, set to detonate if it is tampered with in any fashion. The use of space mines could lead to further destabilization of relations between the superpowers. Further, the Soviet Union has set a historical precedent for the use of such a tactic. Familiar analogies are the Soviet "fishing trawlers" and other vessels that attempt to shadow deployed U. S. task forces and SSBNs.

Another possible Soviet preemptive attack tactic is to use SLBMs or long range cruise missiles to attempt to destroy satellite ground stations and command centers. In the case of a ground based laser architecture, only the power source need be targeted. Conversely, if the Soviets believe the true U. S. goal is defense, then they may choose to slowly degrade the defense rather than attempt a decapitation attack. U. S space assets could be degraded over time by enhanced radiation in the Van Allen belts induced by well placed nuclear explosions. Continually impinging upon the satellites with high power microwaves may also cause significant degradation. As the above representative set shows, the Soviets have a broad range of options open to them, each of which could have a serious impact on the feasibility of BMD.

2. Satellite Defense Options

While a space based ballistic missile defense may be severely hampered by total system ASAT tactics such as nuclear airbursts, the defense does have a number of options available to it to increase individual satellite survivability. However, each of these options presents a

significant tradeoff which must be carefully weighed by the system architect.

Any defensive architecture capable of destroying ballistic missiles and warheads also has the inherent capability of active self defense. Each weapons platform would be able to protect itself and other nearby management satellites from rising ASAT rockets or on-orbit space mines. In addition, each weapons satellite should be able to itself function as an ASAT device, targeted against the Soviet ASAT satellite platforms. The tradeoff involved in active defense is the amount of energy used for self defense versus the amount of energy used towards system goals. The Soviets have the attractive attack option of simply launching numerous attacking ASAT missiles and/or space mines, real or decoy, until the satellite's defensive capability is exhausted. The Soviet ballistic missiles could then be launched unimpeded. This tactic might not be cost effective for the Soviets due competing resources. However, any degree of use of this tactic does, at the minimum, waste precious defensive fuel, electrical energy, or interceptor rockets and therefore decreases overall system effectiveness.

In considering the effectiveness of space mines, it is pertinent to realize that no object can follow another in space without an active station keeping capability. Drag from solar winds and residual atmosphere operates differently on different sized and shaped objects. Therefore, without the ability to maneuver, the space mine and its quarry could drift beyond lethal range in a matter of a few orbits. Thus a space mine would not be a simple remote controlled bomb but rather a large sophisticated device whose presence would be known to the defense almost immediately.

Since space mines cannot be hidden from the defense, the threat posed by the devices could possibly be addressed

politically through the negotiation of "rules of the road" for satellites. The United States could establish and enforce a survivable "keep out" zone around each of its satellites through which no foreign spacecraft could transit without prior arrangements. Any digression would result in the transiting satellite being immediately destroyed. This tactic could be considered to be dynamic hardening of the system.

While the tactic of space denial would be effective against space mines and KEW ASAT devices of limited lethal range, DEW ASAT satellites could not be similarly addressed. Due their long lethal range, the "keep out" zone against DEWs would have to be thousands of miles in diameter and, therefore, the U.S. would literally need the ability to totally dominate space. Since the domination of space is not militarily or politically feasible and since DEW ASATs could cause significant damage before an active self defense could be utilized, other passive survivability measures must also be considered. Passive defense of satellite (DSAT) measures include redundancy, concealment, evasion, and hardening.

The availability of spares, both satellite and ground station, is necessary to insure system reliability when faced with direct attack and the requirement of continual system operations. A large number of spares would also force the offense to spend a great deal of effort to preempt the system. The level of redundancy required is a decision of the system designer that seriously effects overall system cost effectiveness.

Satellite concealment can be affected in a number of ways. The signature of the satellite can be made deceptive to enemy sensors through a combination of electronic, infrared, and stealth techniques. In the case of DEWs, the platforms could be placed in high, remote orbits where they would be difficult to locate. Perhaps the most effective

concealment technique would be the use of satellite decoys. Presenting a large number of target satellites, real and decoy, would force the attacker to either develop a means of effective discrimination or to shift from a preferential to a nonpreferential mode of attack with the resulting loss of leverage. These decoys, however, may be prohibitively costly since not only must they be lifted into orbit but they must also be sufficiently sophisticated to fool the defense.

If a satellite cannot be effectively concealed from attack, then it must either maneuver to evade the attack or meet the attack with self defense and hardening. Satellite maneuvering could be instituted via either ground command or by command of the satellite's own threat sensors. The ability of the satellite to maneuver is constrained, however, by both the amount of fuel and the amount of time available to it. These constraints provide some leverage to the offense. The time constraint shows that maneuvering is not a valid option against DEWs. With kinetic energy or nuclear kill mechanisms, the offense has the attractive option of deploying an array of mines or missiles, real or decoy, about the target satellite which would severely restrict its ability to maneuver away due fuel limitations. This ASAT option would require the defensive satellite to be able to rapidly discriminate the threat objects and change its direction of thrust. The option may also be able to force the defensive satellite away from its required coverage area.

The final passive option is satellite hardening. Current satellites are thought to be hardened to about 1 Joule/cm^2 [Ref. 13: p. 6]. Future satellites can be made much harder by a variety of mechanisms and technologies. The internal components can be easily shielded from KEWs and continuous wave DEWs by armor plating and from pulsed DEWs by multilayer shock coatings with no penalties in weapons

effectiveness. The tradeoff exists in the weight of the shielding material--the more armor placed on the satellite, the larger the cost of lifting the satellite into orbit and the more fuel required to maneuver.

The external components, such as sensors, communications antennas, and mirrors, are more difficult to harden. Concepts being considered include disposable optics and mirrors, meteor shielding against impact attacks, and window shades against IR blinding. The problem in protecting the external components is that the system cannot do its job if it is sealed up. Alternative concepts which may allow continuous operations are therefore also being studied. Hardened RF filters may suffice if the wavelength being protected against is known. Photochromatic optical shields, similar to the flash shields worn by pilots, may also be useful; however, since this technology absorbs light energy, it possibly also may be blinded or burned through by large power levels [Ref. 14: p. 183].

The defensive satellites may have to use a combination of all the above options to insure survivability. A possible decision rule for deciding between self defense, maneuvering, and hardening is to use that option which expends the least mass. For example, if a satellite is faced with a decoyed KE attack, the satellite should maneuver out of the way if the expected mass loss in propellant fuel is minimized. If not, the satellite should either button up and ride through (expend hardening mass) or attempt to shoot its way through (expend weapons mass) [Ref. 13: p. 10]. In conclusion, while an ASAT attack may possibly be countered by a combination of tactics and technologies, the survivability of the defense satellites is a primary issue which provides much of the uncertainty as to the ultimate effectiveness and cost of space based BMD.

B. OFFENSIVE PROLIFERATION

If the Soviets find they cannot preemptively destroy a space based BMD, their next logical step is to attempt to overwhelm or circumvent the defense through a buildup of strategic delivery systems. This action would be counter to the stated SDI goal of reducing the nuclear threat.

A space based defense which cannot penetrate the earth's atmosphere can be circumvented by strategic delivery systems flying within the atmosphere. These underflying systems include bomber aircraft, cruise missiles, and whatever other novel methods time and ingenuity bring forth. This tactic provides both positive and negative tradeoffs to the defense. Although the pace of conflict would become much slower, significant increases to current AAW defenses would be required. Also of concern is that the number of proliferated cruise missiles actually deployed would be difficult to verify.

Another method of underflying the defense is to use SLBMs in depressed, low angle trajectories. While these missiles would still be vulnerable to a satellite BMD, the window of vulnerability would be much reduced and the multiphasing effectiveness would be lessened. The validity of this countermeasure would depend on the threat rate provided by the SLBMs. Note that a defensive satellite constellation properly sized for the instantaneous launch of numerous multiwarhead ICBMs should also be able to effectively address a smaller scale, sporadic SLBM launch unless the window of vulnerability were significantly reduced and/or the number of launch platforms significantly increased. An additional concern brought by this tactic is that the reduced targeting accuracy of SLBMs may force the opponents into the modes of area attack and area defense with the resultant shift in leverage.

The Soviet Union may alternatively attempt to overwhelm the defense through sheer force by proliferating their offensive ballistic missile levels. By inundating the defense, the attacker would hope to either exhaust the defense of its available destructive power or to exceed the defense's maximum kill rate. In order to overwhelm the defense, however, the offense would need specific knowledge of the defense's capabilities and limitations. For example, the offense would need to determine how many "shots" the defense was capable of. This determination may prove difficult in the case of DEWs. Further, proliferation against a defense with a large number of shots may not be cost effective

The offense can increase its threat rate by proliferating in three different ways--by increasing the number of boosters, by increasing the number of warheads per booster, or by utilizing decoys. Intuitively, increasing the number of MIRVs per booster does not appear feasible since this tactic would increase the leverage of boost phase interception. Increasing the number of boosters appears more feasible; however, significant cost tradeoffs arise with this tactic.

The United States could effectively meet the countermeasure of booster proliferation by simply increasing the number of satellites in the boost phase defensive constellation. The sensitivity of the number of boosters (M) in equation 4.8 shows that the number of satellites required goes up in proportion to the square root of the number of missiles. Therefore, large increase in the booster threat rate can be offset by significantly lesser deployments in defensive platforms. Viewing the tradeoff numerically, reconsider the previous example on the number of defensive laser platforms required :

(a) Assume that the U.S. has a boost phase defensive tier of 118 satellites at 90% tier effectiveness and that the Soviets have 1400 ICBMs as an initial state. Therefore, 1400 (.9) = 140 boosters would survive this tier.

(b) Suppose the Soviets want to reestablish a pre-BMD operational scenario for the boost phase (i.e. 1400 boosters are to be delivered to the post-boost phase). The Soviets would now need 1400 / (1 - .9) = 14000 ICBMs and, therefore, would need to build 14000 - 1400 = 12600 new ICBM missiles and silos. The driving result is that, to achieve their goal, the Soviets would have to increase their current force level by a factor of 14000 / 1400 = 10.

(c) According to the square root rule, the United States would have to increase their number of boost phase satellites by a factor of SQRT(10) = 3.16 in order to meet the increased threat. Therefore, 118 (3.16) = 374 boost phase satellites would now be needed causing the U.S. to build an additional 374 - 118 = 256 new satellites.

(d) These results will be favorable to the defense if each of the satellites costs less than 12600 / 256 = 50 times the life cycle costs of an additional ICBM. With numbers like this, the cost tradeoffs would likely favor the defense over the offense.

The final proliferation method available to the Soviets for increasing the target threat rate is to proliferate decoys and other penetration aids. Decoying can be an effective countermeasure simply due the uncertainty the measure brings into the conflict. Additionally, the use of this tactic stresses a defensive system in a number of ways. For example, besides requiring a method and sufficient power to discriminate the targets, each credible decoy requires birth-to-death tracking which may significantly stress

computer battle management. The tradeoff, therefore, is that the usefulness of a decoy to the offense depends on the cost to the defense to either discriminate or destroy it.

Discrimination is difficult within the boost phase. All boost phase interception schemes have a weakness in that any object that behaves like a booster must be intercepted. Due the potential loss of leverage, the defense simply cannot wait until the boost phase is completed to decide which boosters were fakes. As a result, the offense has an attractive option in launching decoy booster rockets. In an attempt to exhaust the defense, the Soviets could construct a massive number of cheap, unhardened silos and a new generation of fake ICBMs, consisting of boosters without costly warheads or precision guidance packages and with no requirement for high reliability. While the cost of this endeavor would be significant to both the offense and defense, the offense would enjoy a significant reduction in boost phase leverage.

Within the post-boost and midcourse phases, many different options become available to both the offense and the defense. The offense may choose any of a number of penaid techniques and technologies. A familiar technique would be the use of chaff in order to provide false radar returns. A similar technique would be the use of IR reflecting aerosol clouds to confuse thermal sensors. An approach which would address radar, infrared, and optical sensors simultaneously would be the use of lightweight balloon decoys. The "balloons" could be made of a thin, metallic skin which would provide the same signature to the sensors as an actual reentry vehicle. Due their light weight, a large number of these balloons could be placed in the bus with little weight penalty. The balloons would be simultaneously deployed along with the reentry vehicles and, in the extreme vacuum at midcourse altitudes, would retain a

trajectory similar to the heavier RVs. With a sophisticated staging technique, the balloons could possibly even enshroud a warhead in a form of antisimulation against discrimination. Another possible option is to develop RVs and penaids with a large variety of signatures to further confuse the defense. Regardless of the method used, the offense must insure the penaids are credible enough to prevent defensive discrimination via simple passive means.

The development and deployment of credible decoys forces the defense to develop efficient methods of active target discrimination. Without good active discrimination, midcourse defense would become nonpreferential with the resultant loss in defensive leverage. The most efficient tactic of discrimination would be to not allow the decoys to be deployed at all. By irridating the buses during post-boost with moderate levels of laser energy, it may be possible to either negate the buses' ability to release the decoys or to destroy the decoys as they are released.

Should the defense not be able to stop the deployment of the decoys, the large midcourse threat cloud would have to be disturbed in some fashion to find the true RVs. One possible method would be to detonate a nuclear blast in front of the threat cloud to sweep away the lighter decoys. This seemingly effective method of bulk filtering does, however, present some tradeoffs to the defense. A high megatonnage nuclear blast in midcourse may cause collateral effects which would interfere with defensive functions. For example, besides possible damage to the midcourse defensive satellites, the IR sensors could be flooded possibly seriously degrading their ability for a period of time.

Alternatively, by actively interrogating individual threat objects, the defense could adopt a simple "shoot-look" tactic for discrimination which would utilize the very technologies being developed for RV kill. Continuous wave

lasers could be used to heat credible objects so the objects could be discriminated by IR sensors based on thermal mass. Pulsed lasers could impart enough force on a lightweight object to cause it to recoil. The change in velocity could then be measured via RF or optical sensors thereby discriminating the light decoys from the heavier reentry vehicles. The reader should note however that, since each object must be interrogated, this tactic causes a return to nonpreferential midcourse defense, although with a much lesser power requirement than if trying to individually destroy each target object.

The above discussion indicates that the credibility of the offensive penaids would depend on rather specific knowledge of the defense's discrimination tactics and technologies. In addition, while penaids may be developed to defeat any one sensor or tactic, to be credible to a defense using a variety of active and passive tactics and technologies the penaids would likely have to be nearly as heavy or sophisticated as an actual warhead. Therefore, the essence of the tradeoff in decoying is that the more efficient the defensive discrimination, the greater the cost to the offense to provide credible decoys. This tradeoff shows that, in the face of efficient discrimination, the offense would have no military or economic incentive to proliferate decoys and, thus, efficient discrimination provides great leverage to the defense. In conclusion, the cost of discrimination versus the cost of decoying is one of the primary cost effectiveness ratios driving the ultimate feasibility of BMD.

C. DEFENSE DEGRADATION

In addition to the aforementioned large scale measures of preemptive attack and offensive proliferation, a great variety of smaller scale countermeasures have been suggested throughout the open literature. These proposed

countermeasures range from the ridiculous to the savvy and from the simple to the technically sophisticated. Two major groupings are evidenced--changes in strategy and changes in technology. A small sampling of the proposed responses should make an impression on the decision maker as to the vast number of different options available to the Soviets in response to a BMD effort.

1. <u>Changes in Launch Strategy</u>

A number of countermeasures become available to the Soviets through changes in their missile launch strategy. The changes would be in either the geographic distribution of the missiles or in the timing of the attack. Possible strategy changes are of great importance to system designers since any change generates great uncertainty and significant tradeoffs in the feasibility of the defensive effort.

The vast majority of Soviet ICBM missile silos are currently spread across the breadth of the Soviet homeland in the vicinity of the Trans-Siberian railway (approximately 55° N latitude). This situation allowed the previous model assumption of uniform missile basing to which the results are very sensitive. The model's sensitivity to the geographic basing provides the Soviets with the attractive strategy option of single point basing. Since the number of satellites required for effective satellite coverage (based on kill rate) increases if all silos are concentrated in one geographic region and decreases if the silos are spread over wide land areas, a strategy of single point basing provides good numerical leverage to the offense.

While point launching is mathematically best for the offense, significant offensive penalties arise from the use of this tactic. Economically, a Soviet decision to abandon their present launch configuration would require a tremendous outlay of funds to build thousands of new silos and command centers. Militarily, point launch greatly increases

the vulnerability of the missiles. Clustered launchings would provide the defense with a bunched threat cloud, thereby allowing for faster retargeting and an increased kill rate. Clustered basing may also allow the defense to prevent the missiles from being launched at all. By detonating nuclear weapons above the silo field, the defense may perform a "nuclear pindown" whereby the missiles would be trapped in their silos. Strategically, single point basing is a readily verifiable configuration which negates the offensive element of surprise. Of final note, the use of this tactic addresses the boost phase in isolation and may ease defensive stress in later tiers.

Another strategic launch countermeasure is to adjust the attack sequence. The timing of the attack, whether via a point basing or spread basing scheme, may prove to be the driving factor in offensive effectiveness. Since highly structured, salvo launches are less effective against a multitiered defensive system, the offense may choose to rapidly, perhaps instantaneously, launch all its missiles in the hope of punching a hole in the defense. This tactic is not, however, without significant tradeoffs. In addition to a bunched threat cloud, simultaneous launch could negate the capability of structured RV arrivals which are necessary to attack the defense in the terminal phase. With some previous knowledge of the defense's capabilities, the offense could conduct specially orchestrated launchings that would force a nonorderly retargeting of a defensive weapon over its entire coverage area. The attack sequencing would also depend on the type of defensive weapon used. For example, an Xray pumped laser cannot target missiles one at a time; therefore, a phased launch sequence could be used to force the defense to decide when to fire most effectively. Before this decision is made, a large number of missiles could get through the boost phase defense.

The above discussion addresses the extremes of the strategic launch options. Other lesser options should also be studied by the system designer. As an example, perhaps single point basing would be not used but rather a small number of silo clusters spread over a wide geographic area. Mobile ICBM launchers may also be considered by the Soviets. However, since global boost phase defenses do not critically depend on prior knowledge of a launcher's position, the distinction between mobile and fixed launchers may not be a factor. Considering attack timing, the weather state may be critical. Clouds, fog, or thick haze may reduce the efficiency of early warning satellites and target sensors. Numerous other strategic launch factors and options could be further identified. In view of this, it becomes obvious that a ballistic missile defense must be designed and sized to address a large range of strategic launch options specifically utilized to fully stress the system.

2. Changes in Boost and Post-Boost Phase Tactics and Technology

Due the great defensive leverage associated with boost and post-boost interception, it is reasonable that the Soviets would devote most of their efforts in developing countermeasures for these phases. The possible Soviet response to boost phase interception that has received the most attention in the open press is the "fast burn" booster. SDI critics have suggested that, should the Soviets develop a solid fueled rocket that could complete boosting while still within the atmosphere, then the potential for advantageous boost phase interception would be seriously diminished. Fast burn rockets would at the minimum compress the window of vulnerability thereby increasing the number of defensive satellites required and could possibly completely close the window to certain technologies such as neutral particle beams and popup Xray lasers.

While this change in technology appears devastating to any BMD effort that relies on boost phase interception, significant deployment tradeoffs arise from the use of this tactic. The critical issue is not how fast the booster burns but rather when the warheads are deployed. Since a high level of warhead placement accuracy is required for surgical attacks against hard point targets, there exists a limit on how low the warheads can be deployed after boosting is completed. Atmospheric density at lower altitudes can significantly degrade reentry vehicle trajectory and final warhead accuracy. Therefore, for the same reason why DEWs cannot target the booster, the bus must wait until it is vulnerable in the upper atmosphere to precisely deploy its warheads.

In addition to reduced warhead accuracy, other deployment tradeoffs arise. The bus cannot deploy any light-weight decoys until it has left the atmosphere; otherwise, the penaids would be readily discriminated due atmospheric drag. Significant weight penalties are also associated with fast burn boosters. The rockets must be strengthened against acceleration and shielded against the increased friction heat; therefore, the missile has less payload available for warheads and penaids. Since this countermeasure tactic addresses only the boost and post-boost phases and may possibly degrade the offense's capabilities against later stages, the effectiveness of fast burn boosters is questionable.

The offense may further attempt to counter boost phase interception by screening the missiles from the space based defense. A variety of screens against different defensive technologies can be established by simply detonating a nuclear weapon in the upper atmosphere. Since such an action would greatly and unpredictably disturb the geomagnetic field, charged particle beam weapons would be rendered

useless. Neutral particle beam weapons would be negated by the principle of "atmospheric heave". A small nuclear warhead exploded at the upper edge of the atmosphere would lift and place a thin layer of air over the rising missiles and into the path of the neutral beam, converting it into a charged beam and thereby causing it to disperse [Ref. 15]. Further, this atmospheric layer would not be dense enough to prevent the deployment of warheads or penaids. Infrared target acquisition sensors can be hindered by developing a strong IR background in the atmosphere just prior to missile launch so the rising missiles would be difficult to find. The utility of creating such an IR background by precursor nuclear burst may, however, be lessened by using sensors that look for a particular wavelength.

Various warhead deployment tactics have been proposed as potential Soviet countermeasures against the post-boost phase. At the beginning of the phase, the reentry vehicle bus could be broken down into several microbuses, each carrying several RVs and a number of penaids. This tactic would provide more targets to the defense, would lessen the leverage of early post-boost intercept, and would shorten the time required to deploy the RVs and penaids. An alternative proposal would be to simply eliminate the post-boost phase through the near simultaneous deployment of all RVs and penaids. By combining this tactic with simultaneous launch, the offense could easily overwhelm a defense sized on threat rate. However, simultaneous release may not be economically feasible to the offense. In order to perform multiple warhead targeting, the current technology bus is simply a small rocket which maneuvers to place each warhead and the various penaids in slightly different trajectories. If, under current technology, all the warheads were released simultaneously, the ability for multiple targeting would be lost. Therefore, to regain the leverage of multiple

targeting under the tactic of simultaneous launch, each warhead and penaid would require its own sophisticated thrust and guidance system. As a result, this tactic would require a substantial increase in missile payload and would cause the penaids to be nearly as sophisticated as the reentry vehicles; thus, this tactic may prove to be economically infeasible.

The offense could attempt to prevent boost and post-boost phase interception by simply hardening the rocket and bus and/or shielding the critical components. The reentry vehicles themselves are already significantly hardened to withstand atmospheric reentry. However, in reality, current technology missiles are probably hardened to less than 1 kJ/cm^2 rather than the 20 kJ/cm^2 previously assumed in the model [Ref. 5: p. 11].

One method of hardening the missile against lasers is to coat the upper rocket stages with an ablative material, such as carbon or silica phenolic. Ablative materials provide a heat shield around the missile which, when heated by laser illumination, burns off carrying away most of the incident laser energy in the combustion gases rather than conducting the energy through to the missile skin. The use of ablative materials would significantly increase the lethal power fluence required to kill the missile; however, the use of ablative materials would also significantly increase the launch weight of the missile and therefore decrease the payload available.

Another technological countermeasure against pulsed lasers would be to use crushable multilayer missile coatings. These layers would capture the impulse wave and stop it from reaching the booster wall. Both of the above hardening countermeasures can be negated by the defense through the use of tailored laser beams. By initially using short laser pulses to burn off the ablative shield or crush

through the multilayer coatings, a continuous wave beam could then be used against the missile skin. Tailored laser beams require the defensive ability to rapidly shift and tune the laser wavelength. This capability may be available in free electron laser technologies.

Neutral particle beam and microwave weapons could be addressed by placing lead shielding around the missile's control electronics. However, since only extremely thick shields would offer any protection, this countermeasure may be economically infeasible. Studies have shown that the lead shield must be at least 1.5 inches thick to offer any protection and therefore the shielding could weigh many tons [Ref. 16].

The offense can dynamically harden the missiles against laser weapons by either reflecting the laser energy away from the missile or by spreading the energy across the missile thereby reducing spot fluence. A missile can be greatly hardened by applying a highly reflective, mirrored coating to its exterior. This measure may not, however, be as simplistic as it seems. Since the surface would become dull due abrasion during the boost ascent, the Soviets could not be certain of the measure's effectiveness. A possible method of solving this deployment problem is to keep the reflective coating covered by a strippable outer wrapper until the booster leaves the lower atmosphere [Ref. 12].

By rotating the missile in flight, the laser energy could be spread more evenly across the missile's surface. A roll of one revolution per second would increase the missile's hardness by approximately a factor of three. Although this tactic would require a large increase in laser power by the defense, several offensive penalties raise. Spinning the missile may seriously complicate the tasks of missile guidance and RV deployment and may require a large degree of missile redesign. Additionally, this tactic would

not be effective against pulsed DEWs and may also not be effective against other DEWs. Due the short kill time required, a slowly revolving missile could be negated be a defensive laser "hot spot" tracking capability.

Other dynamic hardening methods rely on existing devices that can determine whether a target is being illuminated by a laser beam and can spot the direction from which the laser is coming [Ref. 14: p. 182]. An exotic proposal based on this capability is to use a movable, heat absorbing ring which would slide up and down the missile in order to protect the "hot spot". Note, however, that this proposal would require major renovations to the missile and a new series of flight tests. Another proposal would be to develop advanced hydraulic heat exchangers which could be used to distribute the thermal load at the command of the sensor. Both of these proposals would be effective against a DEW technology requiring dwell on target but both would be ineffective against impulse kill.

3. Changes in Midcourse and Terminal Phase Tactics and Technology

Once the offense has successfully launched and deployed all their reentry vehicles and penaids, the dominant defensive problem becomes target location and tracking. The Soviets again have a number of tactical and technological options available to them to compound this problem. An option currently available to the offense is the use of low observable designs and anti-radar coatings in order to make the RVs harder to spot. The tradeoff involved with this tactic is that the new stealth materials typically absorb more light energy than current warhead coverings and therefore the warheads would become more vulnerable to attack.

The offense may choose to complicate the midcourse phase by using varied flight profiles such as non-standard trajectories or non-predictable trajectories. In addition, the offense may desire to maneuver the RVs and penaids to

confuse trackers that depend on precision ballistic trajectories. These actions are not likely to be either economically or strategically feasible for a number of reasons. To precisely maneuver in space would require each RV and penaid to have complex thrusting and guidance systems which may prohibitively add to the system cost. Thrusting the reentry vehicles would also enhance the target's IR signature. Once located, the RV would not be able to maneuver to avoid a directed energy hit due the short kill times associated with DEWs. Further, since a ballistic missile is a very rigid offensive system which must travel in a narrow attack corridor to maintain warhead accuracy, both maneuvering and randomizing trajectories may be strategically infeasible after the boost phase.

Within the terminal phase, the offense loses the leverage associated with lightweight decoys and penaids. To recoup some of this leverage, the Soviets must find some means of placing stress on the terminal defense. By exploding a precursor nuclear warhead over the defense, the offense can attempt to neutralize the defense through radar blackout. However, due the uncertainty as to the effectiveness of the burst in producing radar blackout, the Soviets could not confidently plan an attack depending solely on this effort.

A technological countermeasure which would greatly stress the terminal defense would be the use of maneuverable reentry vehicles (MARVs). A reentry vehicle can be made maneuverable by deploying pop-out control surfaces and tilting its body thereby generating lift. MARVs could alter their course upon atmospheric reentry and attack preprogrammed targets tens to hundreds of kilometers away from their original destination; therefore, MARVs would seriously complicate defensive targeting [Ref. 6: p. 20]. Another technological countermeasure would be the tactic of salvage

fusing. By causing the warhead to detonate once interception is attempted, the IR environment of the upper atmosphere could be substantially flooded thereby degrading the capability of the target sensors. Further, salvage fusing could cause collateral damage to other defensive assets such as rising interceptor rockets.

VII. SUMMARY AND CONCLUSIONS

Throughout this study of the technologies of and countermeasures to ballistic missile defense, a number of salient points became apparent. Each of these points is critical to the ultimate feasibility of a defensive effort :

(1) that the magnitude of the effort will depend on a well defined goal which has yet to be determined. Should the goal be modest, such as merely reducing the number of warheads that impact near population centers, then perhaps more traditional terminal defense methods might suffice. Further, if the goal is to insure a capability for retaliation, then defenses may not be necessary at all since a launch on warning policy would achieve this goal.

(2) that, while the wisdom of developing and deploying a less than perfect defense remains controversial, an imperfect defense may establish a "threshold" of attack intensity, below which the Soviets would not attack due the level of success uncertainty. This concept would itself be a form of nuclear deterrence; therefore, a defense need not be perfect to provide stabilization.

(3) that the most likely Soviet response to a BMD deployment would be a proliferation of forces, both nuclear and conventional and including ASAT and other countering techniques. Although the U.S. seems to enjoy significant cost leverage over the Soviets in the proliferation of ballistic missiles, the Soviets do not have to meet the same cost effectiveness criteria in their economy as does the U.S.

(4) that to realize the protection of a space based BMD, the United States must also increase their AAW defense capabilities and conventional force levels. This factor will have significant impact on the final cost of changing to a defensive posture. Additionally, without a superpower agreement on the resultant levels of conventional weapons, the deployment of a BMD would greatly increase the risk of conventional war.

(5) that the long transition period from a U.S. offensive to defensive posture will be uneasy. Further, during this period, the likelihood of nuclear war may be at its peak.

(6) that, in the long run, a likely Soviet response would be to deploy a matching BMD. The deployment of defensive systems by both sides would cause uncertainties as to the effectiveness of either side's retaliatory capability. These uncertainties could provide pressure for a preemptive strike during crises.

(7) that a complex, space based BMD would require positive control of its operations. The short timelines involved in a ballistic nuclear exchange and the time sensitivity of the defense may require the system to

be capable of totally automated release. The political feasibility of initiating a defense without human interface is highly uncertain. Nonetheless, the defensive system must be sensitive enough so that it is instantaneously available yet under control to such a degree that it is safe from accident when not needed.

(8) that the defense must have a demonstrated reliability. If the defense is to be an effective deterrent to nuclear war, the system must be credible to the Soviets. Therefore, the defensive system must be physically tested to show that it is reliable and effective.

(9) that satellite survivability is a key issue to space based BMD. The defense need not be invulnerable but must be able to maintain a high level of effectiveness when directly attacked.

(10) that the Soviets can seriously complicate the U.S. effort by developing a large variety of countermeasure technologies and tactics.

This study showed that the Soviets have a vast range of countermeasures available to them. These countermeasures may not only be cheaper but could also use simple, current technologies vice the complex, future technologies required for BMD. Additionally, the use of countermeasures would lead to a greater asymmetry of forces between superpowers. However, this is not to say that the U.S. should not consider a technology simply because it has a countermeasure but rather that the U.S. must be aware of what countering options are available to the Soviets for any particular technology. In the least, this knowledge reduces the uncertainties in system research and may possibly allow the U.S. to develop counter-countermeasures to achieve a technological defensive superiority. Towards these ends, the U.S. must continue to identify and study the impact of potential Soviet countermeasures.

In summary, the ultimate utility and cost effectiveness of any proposed ballistic missile defense will depend on the defensive goal, the character of the system, the nature of the attack, and the degree of system effectiveness required. Until these factors are clearly defined and quantified, it would be illogical to renounce the ABM Treaty and SALT

Agreements by proceeding from systems research and analysis to system development.

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